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# HYDRAULIC DESIGN OF DRIP IRRIGATION SYSTEMS

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## CONTENTS


Page

GENERAL DESCRIPTION OF A DRIP IRRIGATION SYSTEM .......... 5
BASIC HYDRAULICS OF A DRIP IRRIGATION SYSTEM .......... 6
Hydraulics of Emitters .......... 6
Hydraulics of Drip Irrigation Lines .......... 7
Pipe Flow Equations for Drip Irrigation Lines .......... 7
Energy Gradient Line for Drip Irrigation Laterals (or Submains) .......... 8
Pressure Variation Along a Drip Irrigation Line .......... 10
Emitter Flow Variation and Uniformity Coefficient of Emitter Flow Along a Drip Irrigation Line .......... 14
DESIGN OF DRIP IRRIGATION LATERAL LINES .......... 17
A General Design Chart for Uniform Slope and Fixed Pipe Size .......... 17
A General Design Chart for Uniform Slope for All Pipe Sizes .......... 22
A Specific Design Chart for Uniform Slope and for a Specific Lateral Line Size (or Emitter) .......... 25
Design Chart for Lateral Lines on Nonuniform Slopes .......... 27
Design Chart for Drip Irrigation Laterals with Varying Pipe Sizes .......... 28
Lateral Design for Emitters Other than the Orifice Type .......... 33
DESIGN OF DRIP IRRIGATION SUBMAINS .......... 35
A General Submain Design Chart for a Single Size on Uniform Slopes .......... 35
A Simplified Submain Design Chart for Single Size on Uniform Downslopes (or Zero Slope) .......... 35
Submain Design for Irregular-Shaped Fields .......... 39
Design of Drip Irrigation Submains with Varying Pipe Sizes .......... 45
DESIGN OF DRIP IRRIGATION MAIN LINES .......... 45
The Energy Gradient Line .......... 45
The Optimal Shape of the Energy Gradient Line .......... 47
A Straight Energy Gradient Line .......... 50
DRIP IRRIGATION EFFICIENCY .......... 54
Emitter Flow Profiles .......... 55
Distribution Efficiency of Drip Irrigation .......... 57
Application Efficiency of Drip Irrigation .......... 58
Design Criterion for a Drip Irrigation System .......... 60

DESIGN OF A DRIP IRRIGATION SYSTEM ................ 61
Design Capacity .................................... 61
Selection and Design of Lateral Lines ..................... 63
Field Layout and the Design of Submains and Main Lines ..... 64
Design Examples .................................... 64
DRIP IRRIGATION SYSTEM DESIGN USING METRIC UNITS . 73
Lateral Line Design Charts for Uniform Slopes .............. 74
A General Design Chart for Uniform Slope for All Pipe Sizes .... 75
Design Chart for Lateral Lines on Nonuniform Slopes ........ 76
Design Charts for Lateral and Submain Design with
Varying Pipe Sizes ................................. 76
Simplified Submain Design Charts ........................ 77
Design Chart for Drip Irrigation Main Lines ................ 77
REFERENCES CITED .................................. 79

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# HYDRAULIC DESIGN OF DRIP IRRIGATION SYSTEMS

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## GENERAL DESCRIPTION OF A DRIP IRRIGATION SYSTEM

Drip irrigation is a method of watering plants frequently and with volumes of water approaching the consumptive use of the plants. This method minimizes such "conventional" losses as deep percolation, runoff, and soil water evaporation. Drip irrigation is accomplished by using small-diameter plastic lateral lines with devices called emitters or drippers at selected spacings to deliver water to the soil surface near the base of the plants.

A drip irrigation system consists of laterals, submains, and main lines. The lateral can be a small plastic tube combined with emitters or simply a small thin-walled plastic tube with orifices. The laterals are designed for distributing water into the field with an acceptable degree of uniformity. The submain acts as a control system that will adjust water pressure to deliver the required amount of flow into each lateral; it is also used to control irrigation time for individual fields. The main line serves as a conveyance system for delivering the total amount of water for the irrigation system.

The emitters, laterals, submains, and main lines are considered the principal parts of a drip irrigation system. There are supporting parts such as filters, flushing units, pressure regulators, pressure gauges, joints and fittings, gate valves, air relief valves, and fertilizer injectors that are used to serve different purposes in a drip irrigation system.

# BASIC HYDRAULICS OF A DRIP IRRIGATION SYSTEM

## Hydraulics of Emitters

Drip irrigation emitters vary from elaborate, variable-flow-rate types to simple orifices or even punched, drilled, or burned holes in the pipe. In general, the flow rate through the emitter is controlled by the hydraulic pressure at the emitter and the flow path dimensions of the emitter. There are three major groups of emitter types: (a) the orifice or nozzle emitter, (b) the long-flow-path emitter, and (c) the pressure compensating emitter.

The orifice or nozzle type usually has fixed emitter geometry so that the flow area is constant. The emitter flow and hydraulic pressure, theoretically, can be shown as

$$q = c\,h^{0.5} \qquad \ldots (1)$$

in which $q$ is the emitter flow rate, in gallons per hour (cubic decimeters per hour); $c$ is a constant; and $h$ is the pressure head, in feet (meters).

The long-flow-path type will be considered as flow in a small microtube. If the area of the flow path is fixed, the emitter flow function can be given as

$$q = c\,h^{x} \qquad \ldots (2)$$

in which $x = 1$ for laminar flow, $x = 0.57$ when flow is considered as turbulent flow in the smooth pipe, $x = 0.54$ when the Williams and Hazen formula (*8*) is used to describe the flow in a small tube, and $x = 0.50$ when the flow is considered as fully turbulent in the small tube.

The pressure compensating emitter is designed so the flow area (orifice or nozzle) adjusts as pressure changes. For example, the flow area will decrease when the pressure increases. The flow area and the hydraulic pressure relationship can be shown as

$$a = b\,h^{-y} \qquad \ldots (3)$$

in which $a$ is the orifice area, and $b$ and $y$ are two constants in the power function. The emitter flow function for this special type of emitter can be shown as

$$q = c\,h^{0.5-y} \qquad \ldots (4)$$

This shows that in the power function, Equation 2, the $x$-value can be made less than 0.5. If the $y$-value is 0.5, then the $x$-value will be zero; this means the emitter is fully pressure compensating, giving a constant flow rate and no changes with respect to the variation of hydraulic pressure.

## Hydraulics of Drip Irrigation Lines

Flow in the drip irrigation lines is hydraulically steady, spatially varied pipe flow with lateral outflows as shown in Figure 1. The total discharge in a drip irrigation line (lateral, submain, or main) decreases with respect to the length of line. The lateral and submain can be considered as having the same hydraulic characteristics and are designed to maintain the smallest pressure variation along the line. The main line is designed based on the input pressure, the required pressure, and the slope of the energy gradient line, which will give a total energy higher than that required at any submain for irrigation.

## Pipe Flow Equations for Drip Irrigation Lines

Drip irrigation lines made of plastic are usually considered to be smooth pipes so the Blasius formula (7) can be used. One empirical

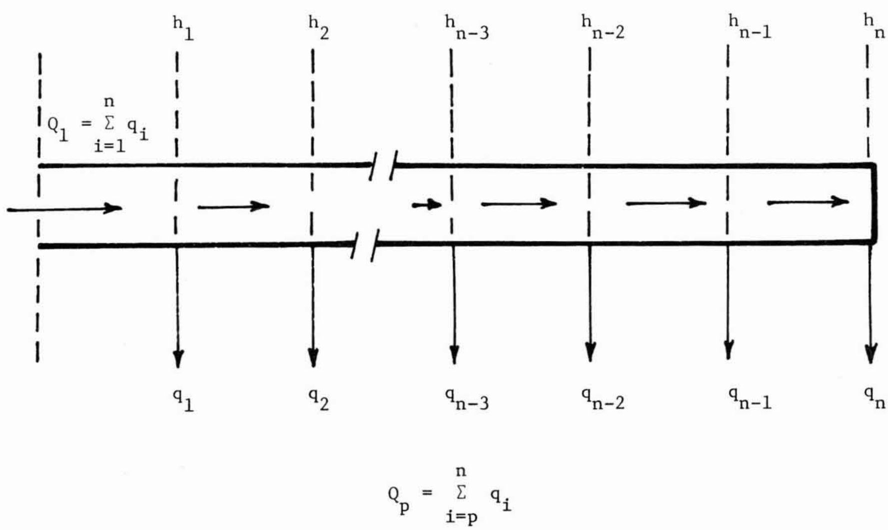



Figure 1. Emitter flow and pressure distribution along a drip irrigation line.

equation frequently used is the Williams and Hazen formula (*8*). As the discharge in the lateral line reduces to zero at the end, there must be a section where laminar flow exists, so the laminar flow equation can be used. The flow in the main line or some sections of the submain may be large enough to reach fully turbulent flow, so the turbulent flow equation can also be used.

In general, the friction drop equation for pipe flow can be shown in simplified form as

$$\Delta H = a\, Q^m\, \Delta L \qquad \ldots (5)$$

where $\Delta H$ is the total energy drop of a pipe section, in feet (meters); $a$ is a constant for a given pipe size and type of flow (or special type of empirical equation used); $Q$ is the total discharge rate, in gpm (lps); $\Delta L$ is the section length, in feet (meters); $m = 1$ for laminar flow, $m = 1.75$ for turbulent flow in smooth pipe, $m = 1.852$ for turbulent flow using the Williams and Hazen formula, and $m = 2$ for a fully turbulent flow where the friction coefficient is constant.

Among all the equations, the Williams and Hazen formula is commonly and most frequently used. The Williams and Hazen formula for smooth pipe (using $C = 150$) can be shown as

$$\Delta H = 9.76 \times 10^{-4} \frac{Q^{1.852}}{D^{4.871}} \Delta L \qquad \ldots (6)$$

in which $\Delta H$ is the energy drop by friction for a given pipe length $\Delta L$, both in feet; $Q$ is the discharge rate, in gallons per minute; and $D$ is the inside diameter (I.D.) in inches. The Williams and Hazen formula also can be shown in metric units as

$$\Delta H = 15.27 \frac{Q^{1.852}}{D^{4.871}} \Delta L \qquad \ldots (7)$$

in which $\Delta H$ and $\Delta L$ are expressed in meters, $Q$ is expressed in liters per second, and $D$ is expressed in centimeters.

## Energy Gradient Line for Drip Irrigation Laterals (or Submains)

As the discharge in the line decreases with respect to the length, the energy gradient line will not be a straight line but a curve of exponential type (*6, 11*). The shape of the energy gradient line can be expressed by a dimensionless energy gradient line (*14*) and can be expressed as

$$R_i = 1 - (1 - i)^{m+1} \qquad \text{. . . (8)}$$

When the Williams and Hazen formula is used for the pipe flow, the dimensionless energy gradient line can be expressed as

$$R_i = 1 - (1 - i)^{2.852} \qquad \text{. . . (9)}$$

in which $R_i = \Delta H_i / \Delta H$ and is called energy drop ratio; $\Delta H$ is the total energy drop at the end of the line or the maximum energy drop, in feet (meters); $\Delta H_i$ is the total energy drop, in feet (meters) at a length ratio $i$ ($i = l/L$); $L$ is the total length of the line, in feet (meters); and $l$ is a given length measured from the head end of the line, in feet (meters). The dimensionless energy gradient lines for different flow conditions are shown in Figure 2; when the Williams and Hazen formula is used, the dimensionless energy line is plotted using Equation 9 (see Figure 2).

The dimensionless energy gradient line will serve as a tool to determine the energy gradient curve when the total energy drop is known. The total energy drop can be determined by using the total discharge (*14*) and can be expressed as

$$\Delta H = -a \frac{Q_t^m}{m+1} L \qquad \text{. . . (10)}$$

in which $Q_t$ is the total discharge at the inlet section. If the average discharge is used the total energy can be expressed as

$$\Delta H = -a \frac{(2Q_a)^m}{m+1} L \qquad \text{. . . (11)}$$

in which $Q_a$ is the average discharge of the line. Equations 10 and 11 show that the total energy drop can be determined by using either the total discharge or the average discharge. If the Williams and Hazen formula is used, the total energy drop can be determined as

$$\Delta H = 3.42 \times 10^{-4} \frac{Q_t^{1.852}}{D^{4.871}} L \qquad \text{. . . (12)}$$

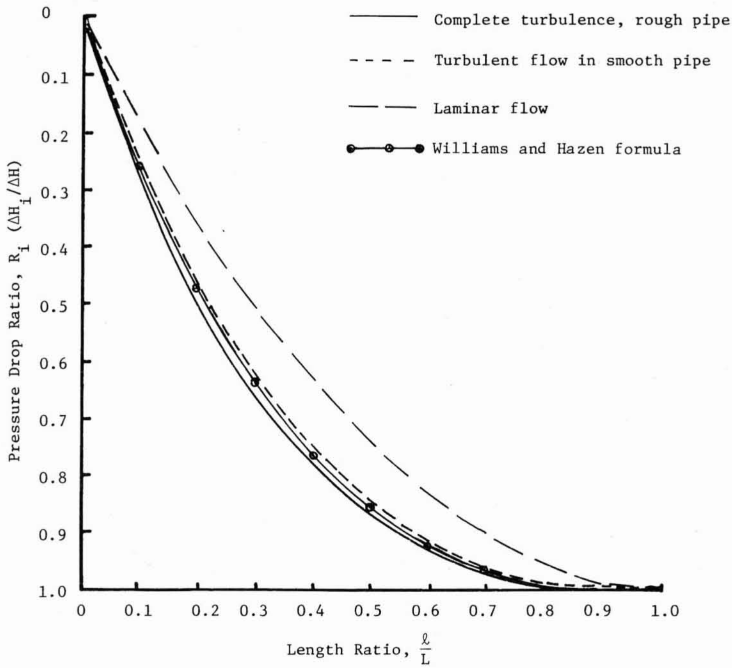



Figure 2. Dimensionless curves showing the friction drop pattern caused by laminar flow, flow in smooth pipe, and complete turbulent flow in a lateral line.

for British units where $Q_t$ is in gallons per minute, $D$ is in inches, and $L$ and $\Delta H$ are in feet, or

$$\Delta H = 5.35 \frac{Q_t^{1.852}}{D^{4.871}} L \qquad \ldots (13)$$

for metric units where $Q_t$ is in liters per second, $D$ is in centimeters, and $L$ and $\Delta H$ are in meters. This confirms the use of the $F$-value as the reduction coefficient (*2, 3*) when a total discharge is used in calculating the total energy drop.

## Pressure Variation Along a Drip Irrigation Line

If a drip irrigation line is laid on level ground the pressure variation along the line will follow the energy gradient curve. If a drip irrigation line is laid on slopes the pressure variation will be affected by the slopes. When the line is laid upslope it will lose pressure, and when the line is laid downslope it will gain pressure. The loss or gain in pressure is linearly proportional to the slope and length of the line.

The total energy at any section of a drip line can be expressed by the energy equation

$$H = z + h + \frac{v^2}{2g} \qquad \ldots (14)$$

where $H$ is the total energy, in feet (meters); $z$ is the potential head, or elevation, in feet (meters); $h$ is the pressure head, in feet (meters); and $v^2/2g$ is the velocity head in feet (meters). The change of energy with respect to the length of line, $L$, can be expressed as (*12*)

$$\frac{dH}{dL} = \frac{dz}{dL} + \frac{dh}{dL} + \frac{d\left(\frac{v^2}{2g}\right)}{dL} . \qquad \ldots (15)$$

Since the outflow from emitters is low in a drip irrigation line, the change of velocity head with respect to the length is small and can be neglected. Therefore, the energy equation can be reduced to

$$\frac{dH}{dL} = \frac{dz}{dL} + \frac{dh}{dL} \qquad \ldots (16)$$

where $dH/dL$ is the slope of the energy line or the energy slope, or

$$\frac{dH}{dL} = -S_f . \qquad \ldots (17)$$

The minus sign means there is friction loss with respect to the line length. The $dz/dL$ represents the slope of the line, as in

$$\frac{dz}{dL} = -S_o \text{ (downslope)} \qquad \ldots (18)$$

and

$$\frac{dz}{dL} = S_o \text{ (upslope).} \qquad \ldots (19)$$

The pressure distribution for a drip irrigation line if it is laid downslope is

$$\frac{dh}{dL} = S_o - S_f . \qquad \ldots (20)$$

The pressure distribution for a drip irrigation line if it is laid upslope is

$$\frac{dh}{dL} = -S_o - S_f . \qquad \ldots (21)$$

Equations 20 and 21 show that the pressure distribution along a drip irrigation line is a linear combination of the line slope and energy slope. With the knowledge of the dimensionless energy gradient line, the friction drop at any given length of the line can be determined when a total energy drop ($\Delta H$) is known. If the length of line and slope are known, the pressure head gain or drop can be determined. The pressure distribution along a drip irrigation lateral, if an initial pressure is given, can be determined as shown in Figures 3 and 4.

The pressure distribution (or variation) along a drip irrigation line in Figures 3 and 4 can be expressed mathematically as

$$h_i = H - \Delta H_i \pm \Delta H_i' \qquad \ldots (22)$$

in which $h_i$ is the pressure expressed as hydrostatic head, in feet (meters), at a given length ratio $i$; $H$ is the input pressure, in feet (meters); $\Delta H_i$ is the total friction energy drop, in feet (meters), at a given length ratio $i$; and $\Delta H_i'$ is the energy gain or loss by slopes (+ sign for downslope, – sign for upslope), in feet (meters), at a given length ratio $i$. Equation 22 can be expressed by using the energy drop ratio $R_i$ from the dimensionless energy gradient line and an energy gain (or loss) ratio by slopes, $R_i'$

$$h_i = H - R_i \,\Delta H \pm R_i' \,\Delta H' \qquad \ldots (23)$$

in which $\Delta H$ is the total energy drop by friction; $\Delta H'$ is the total energy

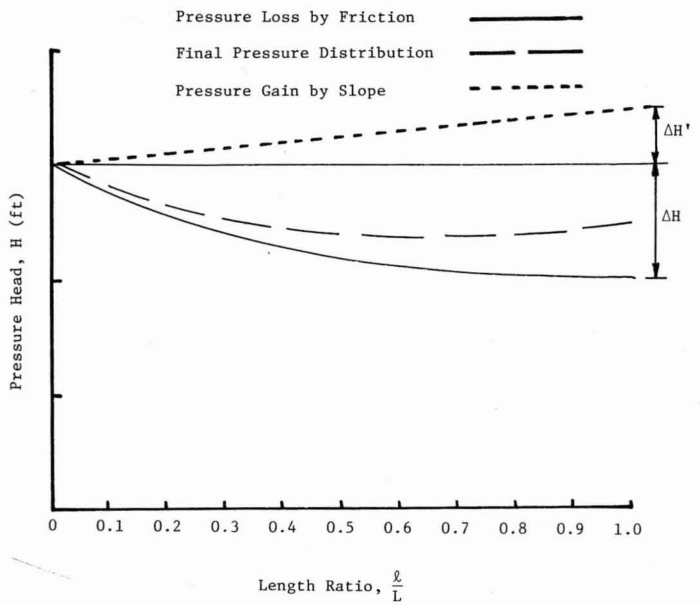



Figure 3. The pressure distribution along a drip irrigation line (downslope).

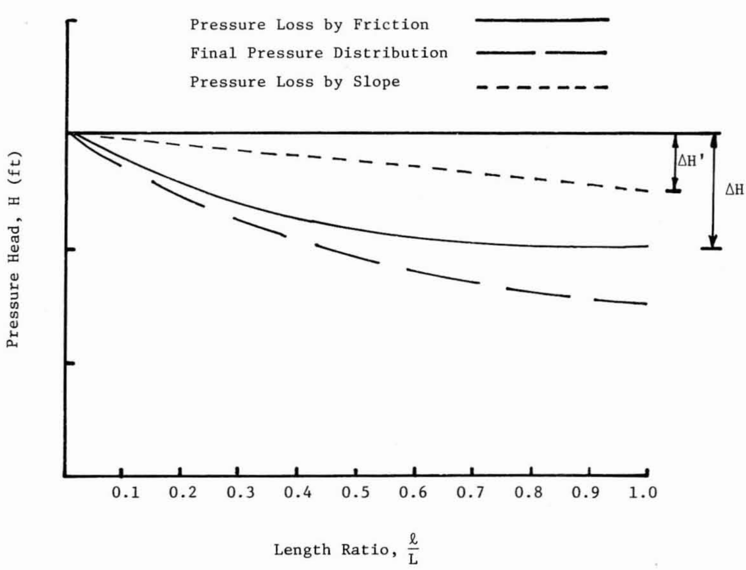



Figure 4. The pressure distribution along a drip irrigation line (upslope).

gain (or loss) by slopes; $R_i = \Delta H_i/\Delta H$; and $R_i' = \Delta H_i'/\Delta H'$. The energy relationship in Equation 23 can be used for both uniform and nonuniform slopes. For uniform slopes, $R_i'$ is the same as the length ratio $i$; the pressure along the drip irrigation line will be

$$h_i = H - R_i \Delta H \pm i \Delta H'. \qquad \ldots (24)$$

If the drip irrigation line is laid on nonuniform slopes, the total length is divided into 10 equal sections, and the slope for each section is determined as $S_1, S_2, \ldots, S_{10}$, then the pressure along the drip irrigation line for nonuniform slopes can be expressed as (*15*)

$$h_i = H - R_i \Delta H \pm 0.1L \sum_1^j S_j \qquad \ldots (25)$$

in which $S_j$ is the slope of the $j$th section along the line using a + sign for downslope and − for upslope; $L$ is the total length of the drip irrigation line; and $i$ and $j$ are related, e.g., $i = 0.7$ and $j = 7$.

## Emitter Flow Variation and Uniformity Coefficient of Emitter Flow Along a Drip Irrigation Line

As shown in Equation 2, the emitter flow is controlled by the hydrostatic pressure at the emitter. This means whenever there is a pressure variation in the drip irrigation line there will be an emitter flow variation along the irrigation line. For an orifice type of emitter and uniform line slope, the emitter flow can be shown as a square root function of the pressure

$$q_i = c \sqrt{H - R_i \Delta H \pm R_i' \Delta H'} \qquad \ldots (26)$$

in which $q_i$ is the emitter flow at a given length ratio $i$. For other types of emitters the proper value of $x$ should be used (Equation 2).

The degree of emitter flow variation can be shown by the uniformity coefficient as defined by Christiansen (*1*) in sprinkler irrigation. The uniformity coefficient for emitter flow variation can be expressed as

$$C_u = 1 - \frac{\overline{\Delta q}}{\overline{q}} \qquad \ldots (27)$$

in which $C_u$ is the uniformity coefficient, $\overline{q}$ is the mean emitter flow, and $\overline{\Delta q}$ is the mean deviation from the mean emitter flow. The uniformity coefficient can be calculated in a simple way by using a dimensionless emitter flow term if an emitter flow $q_o$ related to the operating pressure $H$ (or inlet pressure) is given; therefore

$$\frac{q_i}{q_o} = \sqrt{1 - R_i \frac{\Delta H}{H} \pm R_i' \frac{\Delta H'}{H}} . \qquad \ldots (28)$$

The uniformity coefficient calculated by using terms in Equation 28 will be the same as calculated by using terms in Equation 26.

The uniformity coefficient is a quantitative evaluation of the emitter flow variation. There are other ways of showing the emitter flow variation by simply comparing the maximum emitter flow with the minimum emitter flow. The one that is commonly used defines

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \qquad \ldots (29)$$

in which $q_{var}$ is the emitter flow variation, $q_{max}$ is the maximum emitter flow along the line, and $q_{min}$ is the minimum flow along the line. The relationship between the emitter flow variation as defined in Equation 29 and the uniformity coefficient is determined as shown in Figure 5, which indicates a uniformity coefficient of about 98 percent equals an emitter flow variation of 10 percent and a uniformity coefficient of about 95 percent equals an emitter flow variation of 20 percent.

The pressure variation and emitter flow variation are related by the $x$-value shown in the emitter flow function (Equation 2). The relation can be derived as

$$q_{var} = 1 - [1 - H_{var}]^x \qquad \ldots (30)$$

in which

$$H_{var} = \frac{h_{max} - h_{min}}{h_{max}} \qquad \ldots (31)$$

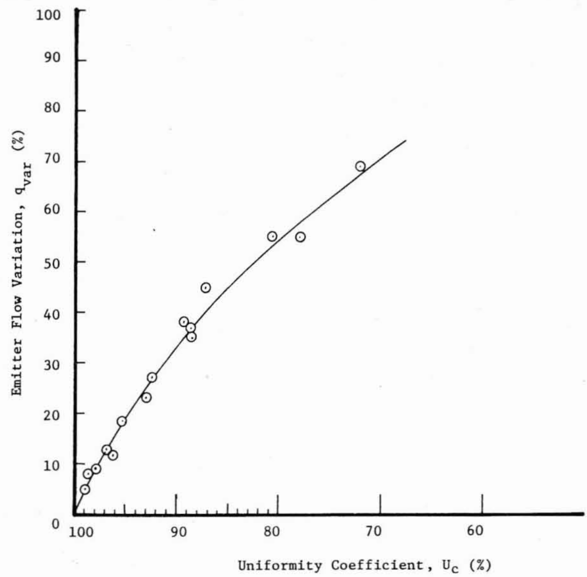



Figure 5. Relationship between emitter flow variation and uniformity coefficient.

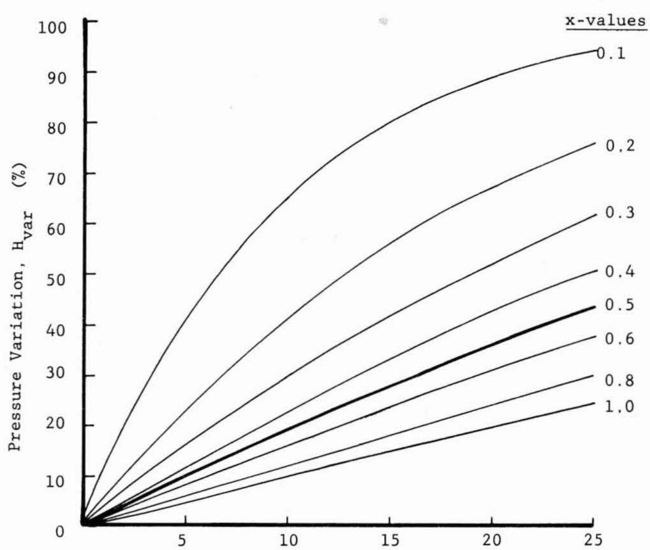



Figure 6. Relationship between emitter flow variation and pressure variation for different $x$-values.

in which $H_{var}$ is the pressure variation, $h_{max}$ is the maximum pressure in the line, and $h_{min}$ is the minimum pressure in the line. The relationship between emitter flow variation and pressure variation for different $x$-values are plotted and shown in Figure 6. When the $x$-value is 0.5, which is true for most of emitters, a pressure variation of 20 percent is equivalent to a 10 percent emitter flow variation, and a pressure variation of 10 percent is equivalent to a 5 percent emitter flow variation.

## DESIGN OF DRIP IRRIGATION LATERAL LINES

In lateral line design, the first consideration is acceptable uniformity of emitter flow or emitter flow variation. The design can be made to achieve a completely uniform emitter flow by using different emitter sizes [orifice diameter (*6*), or microtube length (*4*)], or by using pressure compensating emitters. In general practice, the emitter characteristics are usually fixed, and the emitter flow rate is determined by pressure at the emitter in the line. Hydraulic studies show there are certain to be pressure variations along a drip irrigation lateral due to friction and slope, so there will certainly be emitter flow variations along a lateral line. The major criterion in lateral line design is to design a lateral line, or operating pressure for a given emitter with certain spacing and field slope, to achieve an acceptable emitter flow variation or uniformity coefficient.

### A General Design Chart for Uniform Slope and Fixed Pipe Size

If a lateral line size is fixed and is on uniform slopes, a general design chart made for a given lateral line size and for uniform slopes can be used for designing laterals. A general design chart was made (*12, 13*) in the following steps:

a. A computer program was made for Equation 28 using different combinations of $\Delta H/H$ and $\Delta H'/H$ to calculate the emitter flow ratio $q_i/q_o$. Assuming that the total length of the drip line was arbitrarily divided into 10 sections, the calculation was made by setting the $l/L$ ratio as 0.1, 0.2, 0.3, . . . , 0.9, and 1.0. Using Figure 2, (the curve for the Williams and Hazen equation) or

Equation 9, the energy drop ratio $R_i$ was found to be 0.26, 0.47, 0.64, 0.77, 0.86, 0.93, 0.97, 0.99, 0.999, and 1.0 for each length ratio respectively. The pressure gain (or loss) affected by uniform slopes is linearly related to the length; therefore, the pressure gain (or loss) ratio $R_i'$ is 0.1, 0.2, 0.3, . . . , 0.9, and 1.0, which is the same as the length ratio *i*. For each set of $\Delta H/H$ and $\Delta H'/H$, 10 $q_i/q_o$ ratios can be calculated. By using Equation 27, the uniformity coefficient of the emitter flow (based on the outflow from 10 sections plus the inlet section) can be determined. A total of 10 $\Delta H/H$ from 0.1 to 1.0 and 15 $\Delta H'/H$ from 0.1 to 1.5 was programmed, and a total of 150 uniformity coefficients was calculated. The uniformity coefficient for different sets of $\Delta H/H$ and $\Delta H'/H$ was plotted in Quadrant I of Figure 7. The equal-uniformity lines were plotted as shown in Figure 7.

b. Quadrant II of Figure 7 is designed to show the relationship between $L$ and $\Delta H$ or in a dimensionless form $L/H$ and $\Delta H/H$.

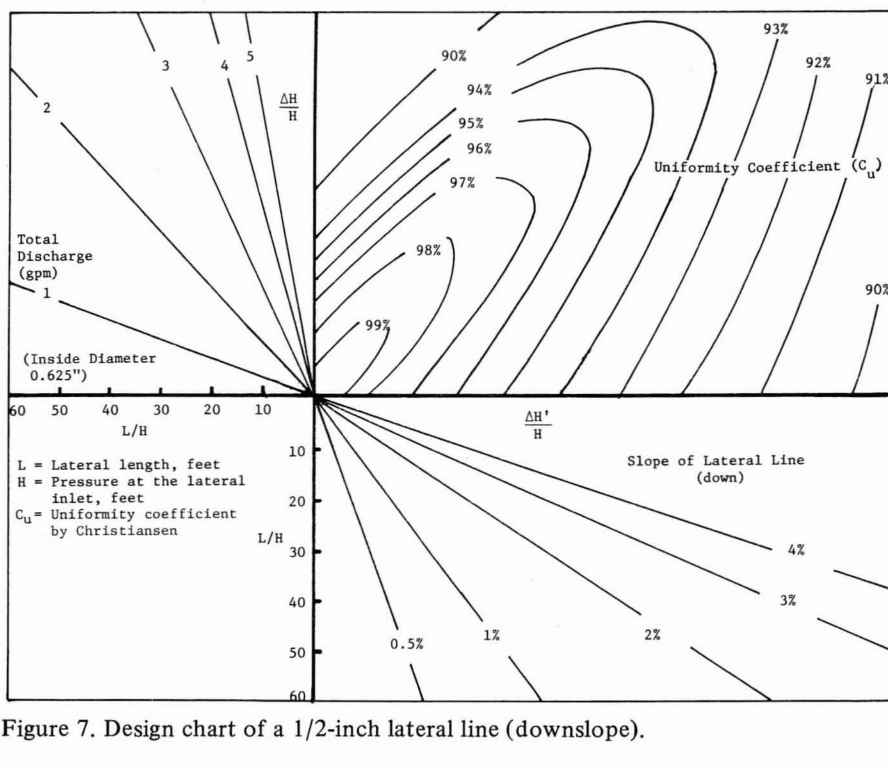



Figure 7. Design chart of a 1/2-inch lateral line (downslope).

This can be calculated by using Equation 12 and put it in a dimensionless form

$$\frac{\Delta H}{H} = 3.42 \times 10^{-4} \frac{Q_t^{1.852}}{D^{4.871}} \frac{L}{H} . \qquad \ldots (32)$$

When the lateral size is fixed, $\Delta H/H$ and $L/H$ will be a linear relationship for a given total discharge $Q_t$. Therefore, different straight lines presenting different total discharges were plotted in Quadrant II of Figure 7. In Figure 7 the calculations were based on a 1/2-inch (0.625 in I.D.) lateral line.

c. Quadrant IV of Figure 7 is designed to show the relationship between $L$ and $\Delta H'$ or in a dimensionless form $L/H$ and $\Delta H'/H$. This can be calculated by the simple slope equation

$$\frac{\Delta H'}{H} = S_o \frac{L}{H} . \qquad \ldots (33)$$

Equation 33 can be plotted as a family of straight lines representing different slopes.

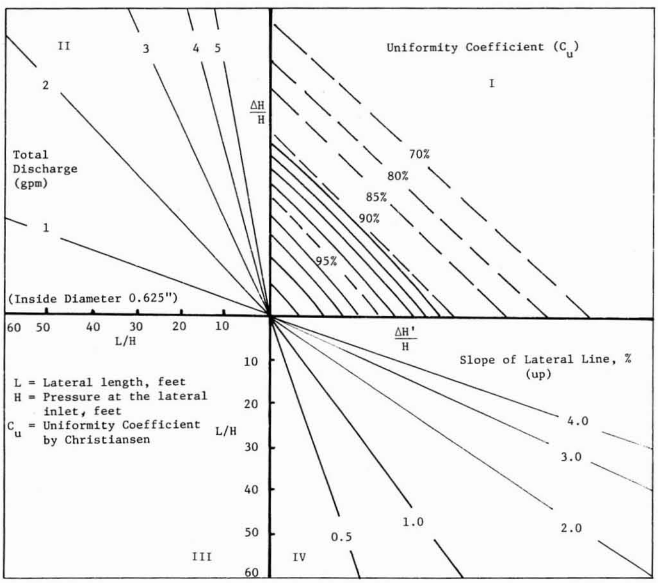



Figure 8. Design chart of a 1/2-inch lateral line (upslope).

d. The design chart was developed by putting Quadrants I, II, and IV together. The designed chart was made for a 1/2-inch lateral line. The design chart as shown in Figure 7 was made for downslopes; the design chart for upslopes was made and is shown in Figure 8.

The design charts as shown in Figures 7 and 8 indicate different uniformity patterns; Figure 7 shows a higher uniformity pattern than Figure 8. It is reasonable to expect the high uniformity pattern for Figure 7 when the energy drop is combined with energy gain from downslopes, whereas, in Figure 8, energy drop is combined with energy loss from upslopes.

In a more practical fashion, because the emitter flow variation is commonly used as design criterion, the design charts are made to show the emitter flow variations. Since the uniformity coefficient and emitter flow variation are related, this can be easily done. A set of design charts showing the emitter flow variations was developed and are shown in Figures 9 and 10.

There is no definite rule about the design criterion (uniformity) to be used in the design. In general practice (*3, 12*) an emitter flow variation of less than 10 percent (related to a uniformity coefficient of 98 percent) is considered as a desirable design; an emitter flow variation of 10 percent through 20 percent (uniformity coefficient 98 percent to 95 percent) is considered as an acceptable design. An emitter flow variation larger than 20 percent (or a uniformity coefficient of less than 95 percent) is not recommended.

The design procedures for using the general design charts Figures 7, 8, 9, and 10 are as follows:

1. Establish $L/H$ and the total discharge, gpm.
2. Move vertically from $L/H$ to the given gpm line in Quadrant II; then, establish a horizontal line into Quadrant I.
3. Move horizontally from $L/H$ to the percent slope line in Quadrant IV; then, establish a vertical line into Quadrant I.
4. The intersection point of these lines in Quadrant I determines the acceptability of the design: uniformity coefficient larger than 98 percent = less than 10 percent emitter flow variations = desirable design; uniformity coefficient from 98 percent to 95 percent = 10 percent to 20 percent emitter flow variation = acceptable design; uniformity coefficient of less than 95 percent = emitter flow variation larger than 20 percent = design not recommended.

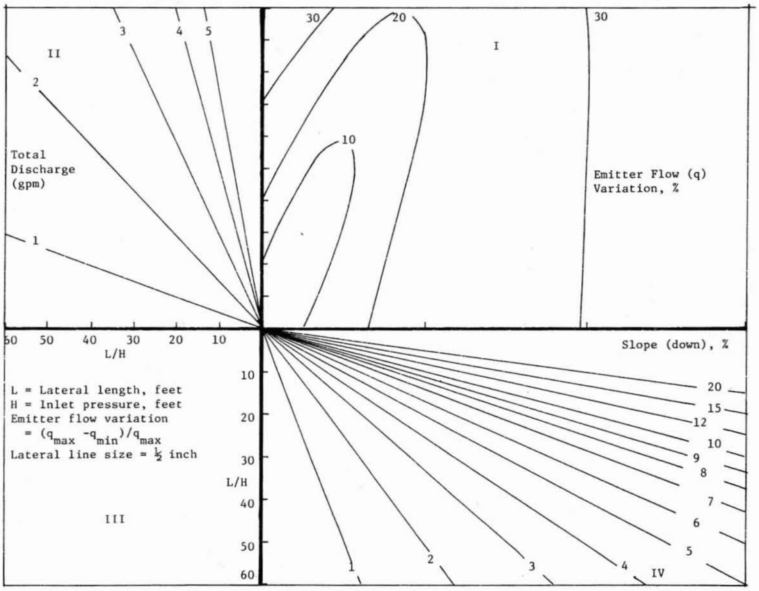



Figure 9. Design chart for a 1/2-inch lateral line (downslope).

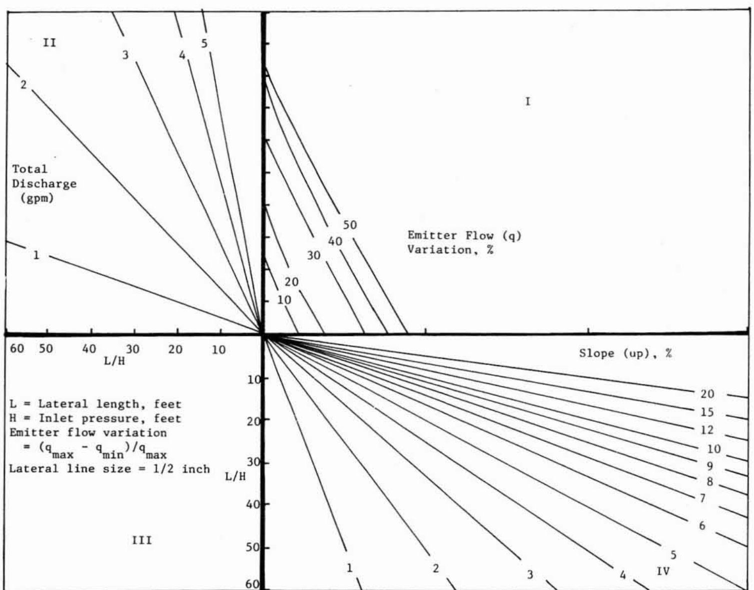



Figure 10. Design chart for a 1/2-inch lateral line (upslope).

## A General Design Chart for Uniform Slope for All Pipe Sizes

The above mentioned design charts are made for a specific lateral line size (1/2-inch). This set of charts is commonly used because most of lateral lines are made as 1/2-inch. If a lateral size other than 1/2-inch will be used, another set of charts can be made by using the desired lateral size in Equation 32 and making a new set of discharge lines in Quadrant II of Figures 7 and 8.

A dimensionless chart was developed by simply using the following relationship in Quadrant II of Figures 7 and 8

$$\frac{\Delta H}{H} = \frac{L}{H} \cdot \frac{\Delta H}{L} \quad \ldots (34)$$

This relationship shows a set of straight lines for different values of $\Delta H/L$ in Quadrant II. $\Delta H/L$ is the ratio of total energy drop to the total length of the line. $\Delta H$ can be determined from Equation 12 (British units) or from Equation 13 (metric units).

A set of dimensionless general design charts for uniform downslopes and upslopes was plotted and is shown in Figures 11 and 12. Two support monographs were plotted for Equations 12 and 13 and are shown in Figures 13 and 14. This set of figures (Figures 11, 12, 13, and 14) can be used for lateral line design for any size of lateral line and for either British or metric units. They can be used to check the design when a lateral line size is given, and they can also be used to design the proper lateral line size. The design procedures are:

a. To select proper lateral line size:
   1. Establish a trial $L/H$ in Figure 11 or 12.
   2. Move horizontally from $L/H$ to percent slope line in Quadrant IV; from that point establish a vertical line into Quadrant I.
   3. Establish a point along this line in Quadrant I at the upper boundary of desirable zone (A) or acceptable zone (B) depending on the design criterion; from that point establish a horizontal line into Quadrant II.
   4. Establish a vertical line in Quadrant II from the $L/H$ value so that it intersects the horizontal line of item 3 at a point.
   5. Determine the $\Delta H/L$ value in Quadrant II at this point.

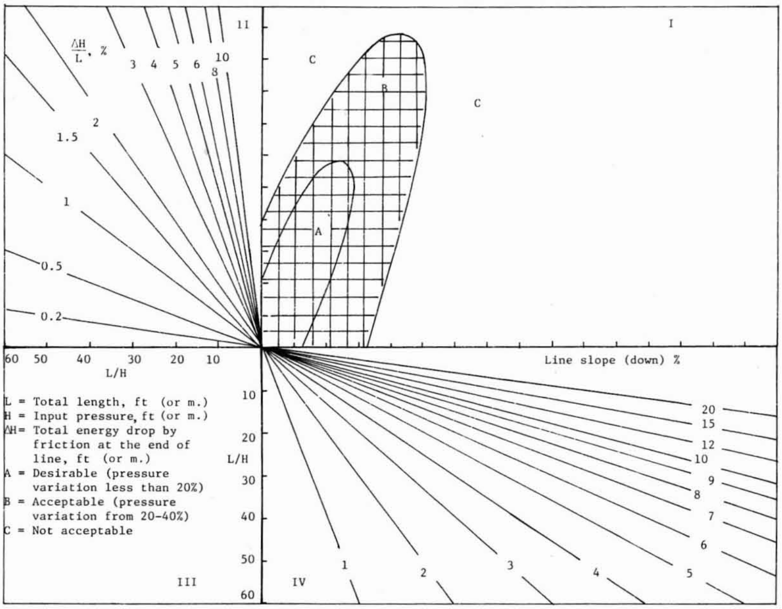



Figure 11. Dimensionless general design chart (downslope).

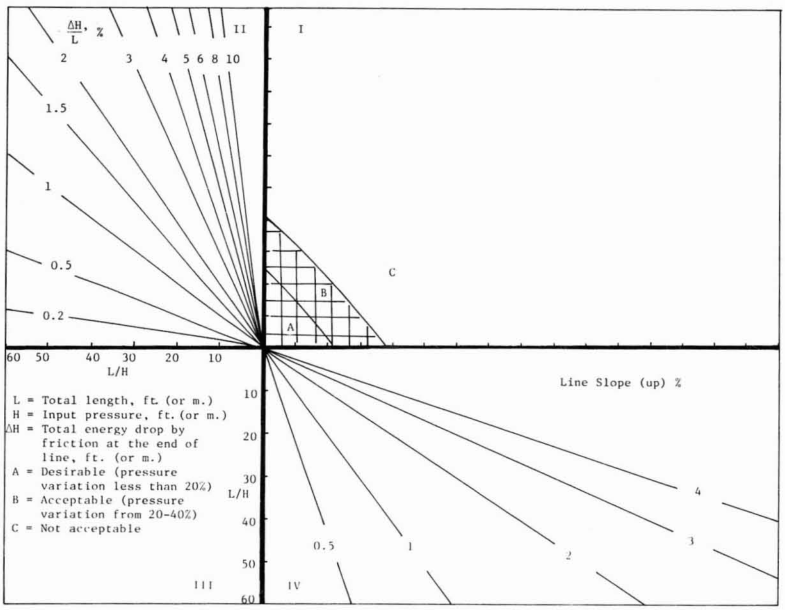



Figure 12. Dimensionless general design chart (upslope).

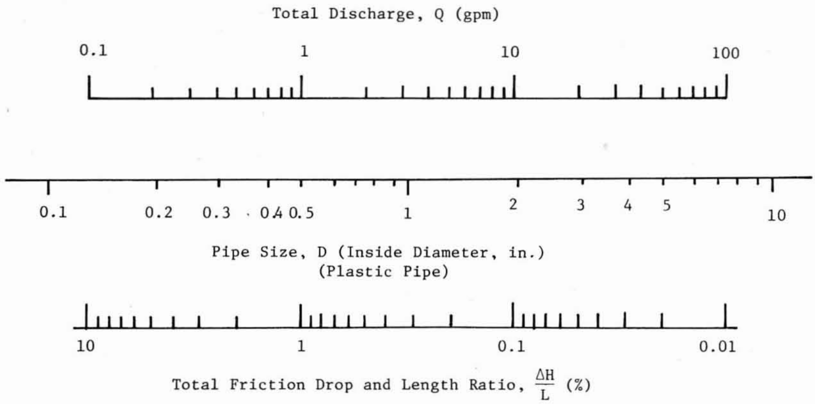



Figure 13. Nomograph for drip irrigation laterals and submain design in British units.

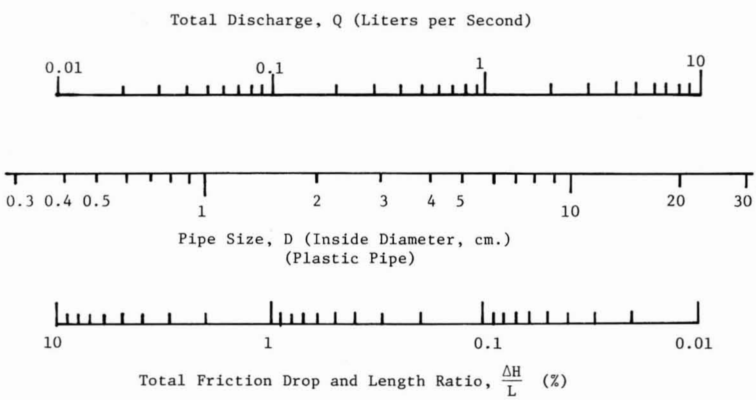



Figure 14. Nomograph for drip irrigation laterals and submain design in metric units.

6. From the proper nomograph (Figure 13 or 14) using total discharge and $\Delta H/L$, establish the minimum lateral size acceptable (20 percent pressure variation if zone A is used, 40 percent pressure variation if zone B is used).

b. To check acceptability of a given lateral line:
   1. Establish a trial $L/H$ and total discharge.
   2. From the proper nomograph (Figure 13 or 14) use the total discharge and lateral line size to determine $\Delta H/L$.

3. Move vertically from $L/H$ to the determined $\Delta H/L$ in Quadrant II of Figure 11 or 12; then establish a horizontal line into Quadrant I.
4. Move horizontally from $L/H$ to the percent slope line in Quadrant IV; then establish a vertical line into Quadrant I.
5. The intersection point of these lines in Quadrant I determines the acceptability of the design.

## A Specific Design Chart for Uniform Slope and for a Specific Lateral Line Size (or Emitter)

The general design charts presented in the previous two sections can be used for any type of lateral or emitter. However, it requires trials of $L/H$. An optimal design (based on a preset design criterion) can be achieved by only a few trials. Under certain conditions, if a special type of emitter is frequently used, one may wish to develop a specific design chart just for that lateral or emitter. This is the so-called specific design chart that can be developed based on a computer simulation. A specific design chart is made according to the following plan (*10*):

a. Determine the emitter flow and hydraulic pressure relationship for the given lateral line or emitter as shown in Equation 2.
b. Develop a computer program to calculate the pressure variation for the specific emitter, a given emitter spacing, and lateral line size. The computer program will calculate pressures starting from the downstream point with a specified pressure. Every small section between two emitters is considered as a pipe flow calculation. The energy drop $\Delta H$ for the each small section can be determined based on all the flow conditions (laminar, transition, or turbulent) or simply using the Williams and Hazen formula. The energy equation used in the program can be Equations 20 and 21, or can include the velocity head term $v^2/2g$. It was found that, with or without using $v^2/2g$ in the calculation, there will be no significant difference in the result. Also, it was found that the use of the Williams and Hazen formula in calculating energy drop $\Delta H$ will give almost same results as calculated by the energy drop equations for different flow conditions.
c. When a design criterion such as a 10 percent emitter flow variation

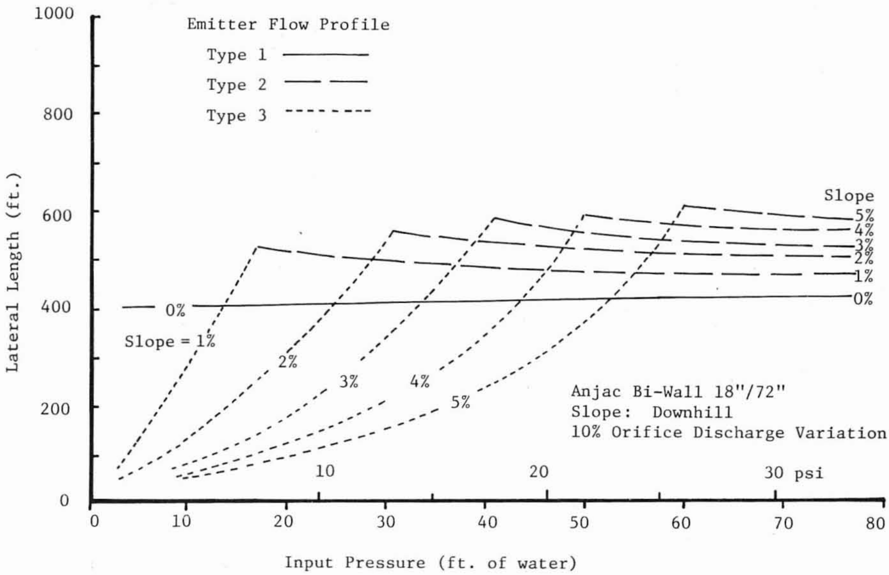



Figure 15. Design chart for Anjac Bi-Wall 18″/72″ laid on downhill slopes.

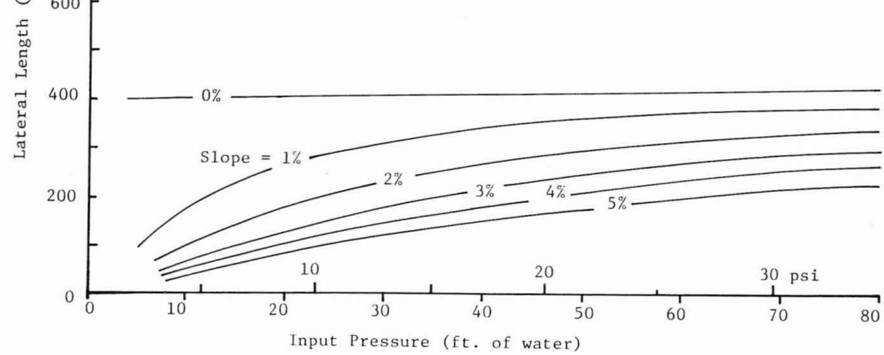



Figure 16. Design chart for Anjac Bi-Wall 18″/72″ laid on uphill slopes.

(or a 20 percent pressure variation) is set, the computer program will determine the lateral line length for different input pressure and line slope (uniform) conditions. The length determined is the design length for which the emitter flow variation is 10 percent according to the design criterion.

d. The specific design charts can be plotted as shown in Figures 15 and 16. The design chart shown in Figure 15 is for downslope conditions; Figure 16 is for upslope conditions.

The specific design charts may be used with a given slope to determine either the maximum lateral length for a given input pressure or the minimum input pressure for a given length.

**Design Chart for Lateral Lines on Nonuniform Slopes**

The design charts developed in the previous three sections were limited to uniform slopes and are applicable to small vegetable plots, orchards on uniform slope terrain, or even for big sugar plantations if the lateral lines are designed considering the contours. For areas with rough terrain, usually in hills for tree crops, field layouts of drip irrigation systems are frequently on nonuniform slopes. The design principles for lateral line design on uniform slopes or nonuniform slopes are the same. The pressure distribution (or variation) along the lateral line is determined based on a linear combination of energy drop by friction and energy gained (or lost) by slopes as given by Equations 20 and 21, or it can be determined by a graphic solution as shown in Figures 3 and 4, except that nonuniform slope conditions will be used.

A dimensionless chart was developed (*15*) for lateral line design on nonuniform slope situations as shown in Figure 17. Figure 17 consists of four quadrants. Quadrant I is designed for plotting the nonuniform slope pattern in a dimensionless form as a length ratio $i = l/L$ versus $\Delta H_i'/L$. Quadrant II shows the energy drop pattern for different $\Delta H/H$ values; for a given $\Delta H/H$ value the $\Delta H_i/H$ values can be determined for any length ratio $i$. Quadrant IV is designed to convert the dimensionless term $\Delta H_i'/L$ to $\Delta H_i'/H$ for different combinations of the design parameter $L/H$ (length and head ratio). Quadrant III is used to check the pressure variation by balancing the friction drop $\Delta H_i$ (expressed dimensionlessly as $\Delta H_i/H$) and energy change by slopes $\Delta H_i'$ (expressed dimensionlessly as $\Delta H_i'/H$) for all sections along the lateral line. A 45-degree straight line from the origin (zero length point) will show a zero variation from the operating pressure. Lines for 10, 20, and 30 percent variation for both sides of the zero variation line were also plotted and are shown in Quadrant III.

The design procedure is as follows:

1. Divide the nonuniform profile into several sections in which each section can be considered as a uniform slope; determine the slope of each section; calculate the energy gain (or loss) for each section due to its slope; and find the total energy gain by slopes for any given length along the line ($\Delta H_i'$).
2. Plot the nonuniform slope pattern in a dimensionless form ($l/L$ versus $\Delta H_i'/L$) in Quadrant I.
3. Determine the total energy drop by friction $\Delta H$ from Equations 12 or 13 or by using the nomographs as given in Figures 13 or 14 and calculate $\Delta H/H$.
4. Determine the length and head ratio $L/H$.
5. Pick a point from the nonuniform slope profile in Quadrant I—usually a point between two slopes, or a point in the middle of the section.
6. From that point draw a vertical line downward to the determined $L/H$ in Quadrant IV; then establish a horizontal line into Quadrant III; also from that point draw a horizontal line to the determined $\Delta H/H$ in Quadrant II; then establish a vertical line into Quadrant III.
7. The location of the intersection point of these two lines in Quadrant III will determine the pressure variation from the operating pressure $H$.
8. Repeat the same procedure for other points along the dimensionless nonuniform slope profile in Quadrant I; the pressure variation along the entire lateral line can then be obtained.

The design chart shown in Figure 17 can be made into a slide rule for engineering design.

## Design Chart for Drip Irrigation Laterals with Varying Pipe Sizes

Most drip irrigation laterals are designed for a single size. The energy gradient line for a single size has been derived and applied to lateral

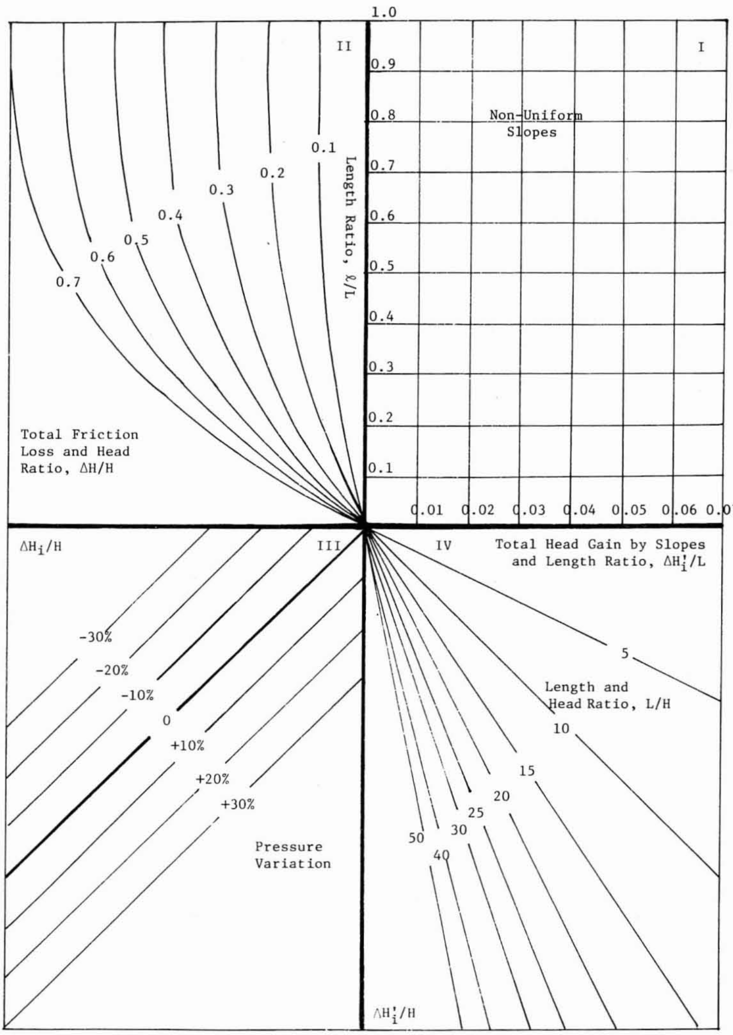



Figure 17. Design chart for nonuniform slopes.

designs such as those design charts developed in previous sections. However, under certain field conditions the lateral length may be relatively long and laid on either uniform or nonuniform slopes. This lateral line may be designed using a series of different pipe sizes (different diameters) (*16*).

It has been shown that if the lateral line having a single size is designed so that the total energy drop by friction $\Delta H$ is balanced by the energy gain by downslope, $\Delta H'$, at the end of the line, there will be a maximum pressure difference of 0.36 $\Delta H'$, or 0.36 $S_o L$, where $S_o$ is the lateral line slope (uniform slope) and $L$ is the total length. This is due to the curved shape of the energy gradient line as shown in Figure 2.

If a lateral line is divided into sections and different lateral sizes can be used, the energy gradient line will be closer to the straight line representing energy gain by slope; therefore, the pressure difference will be reduced. This can be shown from a dimensionless plot, Figure 18, in which it is clear that the energy gradient curves are closer to a straight line when varying sizes of lateral line can be used. It can be seen that if two equal sections are used and two different lateral line sizes are designed based on the line slope (uniform slope), the maximum pressure difference will be reduced to 0.18 $\Delta H'$ or 0.18 $S_o L$, which occurs near the middle of the second section. If four equal sections are used and four different pipe sizes are designed based on the line slope

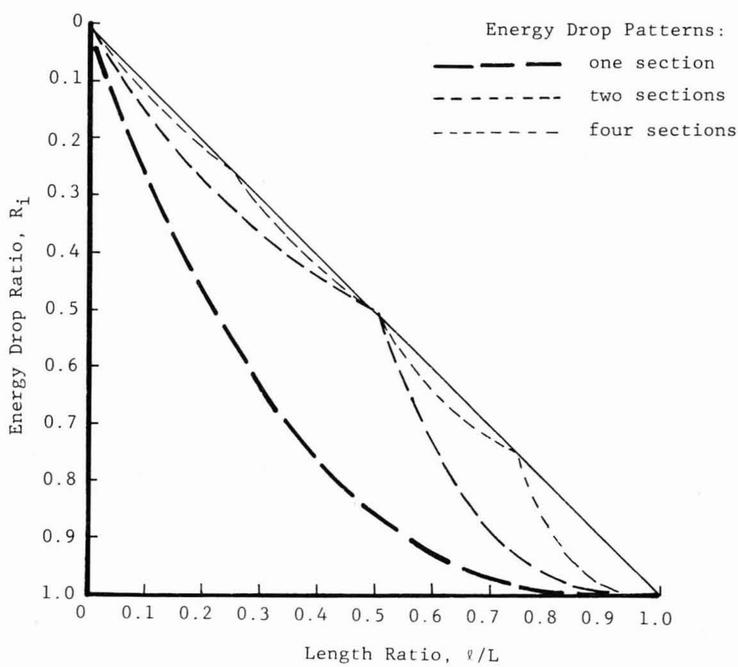



Figure 18. Dimensionless energy gradient lines for irrigation lines with varying sizes.

(uniform slope), the maximum pressure difference will be reduced to 0.09 $\Delta H'$ or 0.09 $S_o L$, which occurs near the middle of the last section.

This approach also can be used for nonuniform (downslope) situations. If the slopes of the several sections of the nonuniform slope profile are used to design the lateral line size for each section, the pressure difference can be determined as follows:

a. Two equal sections with downslopes $S_1$ and $S_2$:
   The maximum pressure difference for the first section can be determined as 0.14 $S_1$ (0.5 $L$). The maximum pressure difference for the second section is 0.36 $S_2$ (0.5 $L$). All the differences are shown in Figure 18.
b. Four equal sections with downslopes $S_1$, $S_2$, $S_3$, and $S_4$:
   As shown in Figure 18, the maximum pressure differences for sections 1, 2, 3, and 4 are 0.06 $S_1$ (0.25 $L$), 0.09 $S_2$ (0.25 $L$), 0.14 $S_3$ (0.25 $L$), and 0.36 $S_4$ (0.25 $L$), respectively.

The total energy drop for each section can be determined by using the mean discharge in the section without causing much error; the Williams and Hazen formula can be used for calculating the total energy drop $\Delta H$

$$\Delta H = 9.76 \times 10^{-4} \frac{Q_{\text{mean}}^{1.852}}{D^{4.871}} L \qquad \ldots (35)$$

and since the design is made for $\Delta H = \Delta H'$, Equation 35 can be shown as

$$S = 9.76 \times 10^{-4} \frac{Q_{\text{mean}}^{1.852}}{D^{4.871}} \qquad \ldots (36)$$

where $S$ is the slope of a given section, $Q$ is expressed in gallons per minute, and $D$ is expressed in inches. Equation 36 can be presented as a nomograph as shown in Figure 19. The nomograph can also be made for metric units using the equation

$$S = 15.27 \frac{Q_{\text{mean}}^{1.852}}{D^{4.871}} \qquad \ldots (37)$$

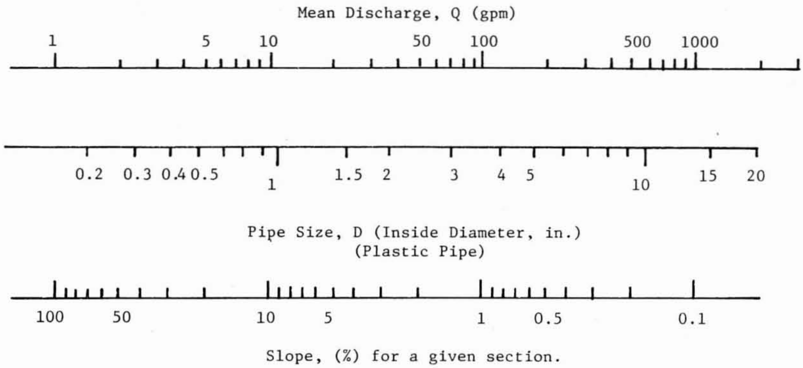



Figure 19. Nomograph for drip irrigation submain and lateral design in British units (for multiple sections with varying sizes).

NOTE: Calculated by Williams and Hazen formula, $C = 150$.

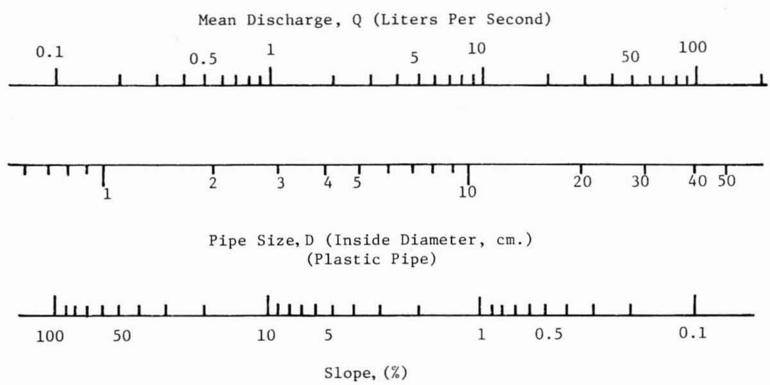



Figure 20. Nomograph for drip irrigation submain and lateral design in metric units (for multiple sections with varying sizes).

NOTE: Calculated by Williams and Hazen formula, $C = 150$.

in which $Q$ is expressed in liters per second and $D$ is expressed in centimeters. The nomograph for metric units is shown in Figure 20.

The design procedure for designing laterals with varying sizes is as follows:

1. Divide the lateral line profile into several sections in which each section can be considered as a uniform slope.

2. Find the slope of each section; there may be $S_1$, $S_2$, $S_3$, and $S_4$ (if four sections are used) for nonuniform situations or a single slope $S$ for a uniform slope.
3. Determine the mean discharge, $Q_{mean}$, for each section.
4. Use the proper nomograph to determine the lateral line size for each section. This can be done by drawing a straight line on the nomograph from the mean discharge to the slope. The lateral line size can then be read from the straight line at the intersection point on the lateral size line in the nomograph.

The design charts shown in Figures 19 and 20 can be made into slide rules for engineering design.

## Lateral Design for Emitters Other than the Orifice Type

As mentioned in the section on the hydraulics of emitters, the $x$-values in the emitter flow and pressure function as given in Equation 2 can be either smaller or larger than a square root function, $x = 0.5$. There are some long-flow-path type of emitters that may have an $x$-value larger than 0.5. There is no emitter with an $x$-value less than 0.5 unless it is specially designed. The general design charts presented previously can be used in the design if a relationship between the pressure variation and emitter flow variation can be specified.

The relationship between emitter flow variation, $q_{var}$, and pressure variation, $H_{var}$, is shown in Equation 30 and is given in Table 1.

**Table 1. Pressure variations for different emitter flow variations and $x$-values**

| | Emitter Flow Variation | | | | |
|---|---|---|---|---|---|
| $x$-value | 5% | 10% | 15% | 20% | 25% |
| | (%) | (%) | (%) | (%) | (%) |
| 0.1 | 40 | 65 | 80 | 89 | 94 |
| 0.2 | 23 | 41 | 56 | 67 | 76 |
| 0.3 | 16 | 30 | 42 | 52 | 62 |
| 0.4 | 12 | 23 | 33 | 43 | 51 |
| 0.5 | 10 | 19 | 28 | 36 | 44 |
| 0.6 | 8 | 16 | 24 | 31 | 38 |
| 0.7 | 7 | 14 | 21 | 27 | 34 |
| 0.8 | 6 | 12 | 18 | 24 | 30 |
| 0.9 | 5.5 | 11 | 17 | 22 | 27 |
| 1.0 | 5 | 10 | 15 | 20 | 25 |

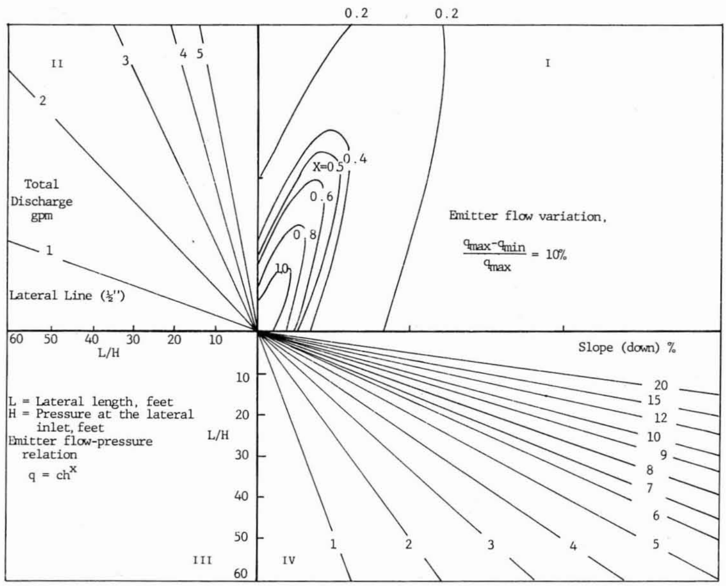



Figure 21. Design chart for different $x$-values for emitter flow variation of 10 percent.

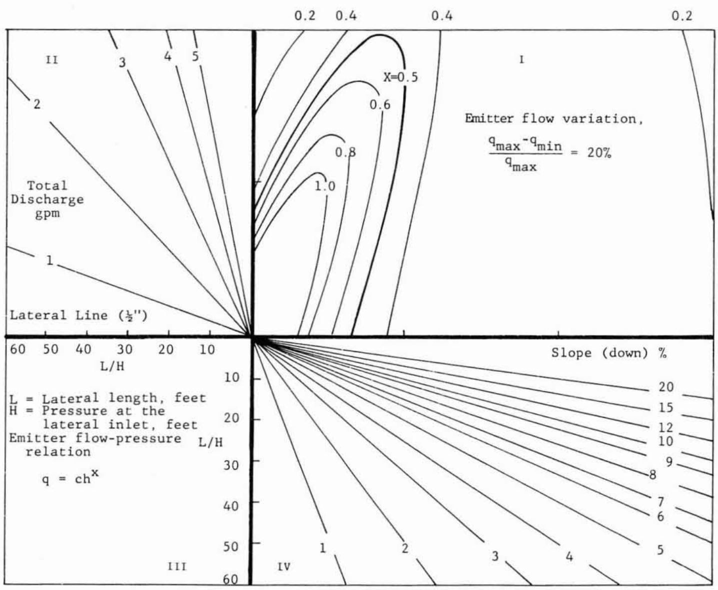



Figure 22. Design chart for different $x$-values for emitter flow variation of 20 percent.

Design charts can be made by setting a design criterion (emitter flow variation) and plotting the equal-emitter flow variation lines for their corresponding $x$-values. A set of 1/2-inch lateral line design charts for 10 and 20 percent emitter flow variation (downslopes) for different $x$-values are given in Figures 21 and 22. The design procedure will be the same as for the general design charts.

## DESIGN OF DRIP IRRIGATION SUBMAINS

The design of submains is based on both capacity and uniformity. Capacity means the submain size should be large enough to deliver the required amount of water to irrigate the field. Uniformity means the submain should be designed to maintain an allowable pressure variation so the flow into all lateral lines will have little variation.

The submain, hydraulically, is the same as a lateral line having a steady, spatially varied flow with lateral outflows. Design of a submain will be based on the study of hydraulics and energy relations. Some of the developed design charts for lateral lines also can be used for submains.

### A General Submain Design Chart for a Single Size on Uniform Slopes

This set of design charts for submain design is the same as presented in the section on a general design chart for uniform slope and shown in Figures 11, 12, 13, and 14. The same design procedure can be used. The only difference is the calculation of total discharge. In case of the submain design, the total discharge is the summation of all the lateral line discharges.

### A Simplified Submain Design Chart for Single Size on Uniform Downslopes (or Zero Slope)

Since the length of a submain is relatively short (less than 200 feet) the design can be made by considering that the total energy drop from friction is equal to the total energy gain by slope, $\Delta H = \Delta H'$ (*17*). Generally, this design can achieve a high uniformity of lateral discharge along the submain. When the $\Delta H$ is made equal to $\Delta H'$, Equation 12 can be written as

$$\Delta H' = 3.42 \times 10^{-4} \frac{Q^{1.852}}{D^{4.871}} L \qquad \ldots (38)$$

or

$$S_o = 3.42 \times 10^{-4} \frac{Q^{1.852}}{D^{4.871}} \qquad \ldots (39)$$

in which $S_o$ is simply the submain slope. When Equation 39 is used, the maximum pressure difference will be near the middle section of the submain with a magnitude equal to 0.36 $\Delta H'$. In order to be sure that the maximum pressure difference 0.36 $\Delta H'$ is less than 20 percent pressure variation to maintain a lateral discharge variation of less than 10 percent, it is necessary to check the following relationship

$$H_{\text{var}} = \frac{0.36\ \Delta H'}{H} < 20\% \qquad \ldots (40)$$

or

$$H_{\text{var}} = \frac{0.36\ L\ S_o}{H} < 20\%. \qquad \ldots (41)$$

When $H_{\text{var}}$ is set as 20 percent, then

$$\frac{0.36\ L\ S_o}{H} = 20\%. \qquad \ldots (42)$$

This means that for a given combination of $L/H$, a maximum slope can be found for maintaining the pressure variation at 20 percent. Any slope less than the maximum means the pressure variation will be less than 20 percent. Equation 42 was plotted for determining maximum slope as shown in Figure 23. The simple submain design chart can be plotted from Equation 39 and is shown in Figure 24. Figure 24 can be used to design the submain size from the total discharge and the submain slope when the slope is first checked and found to be less than the maximum slope in Figure 23.

The simple submain design chart in Figure 24 is designed for slopes equal to or larger than 0.5 percent. When the slope is less than 0.5 percent it is considered as level or zero slope, for which Equation 39 cannot be used. Under this condition it is assumed that the pressure

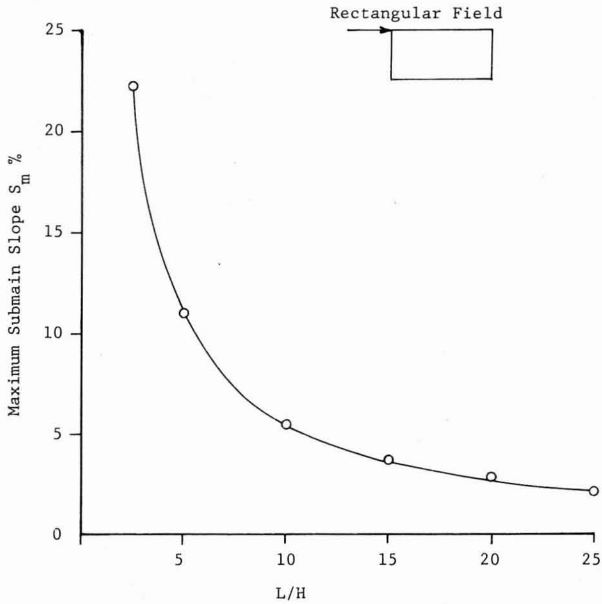



Figure 23. Maximum submain slope to maintain a 20 percent pressure variation when slope is used for submain design (simplified design chart, Figure 24, for rectangular field).

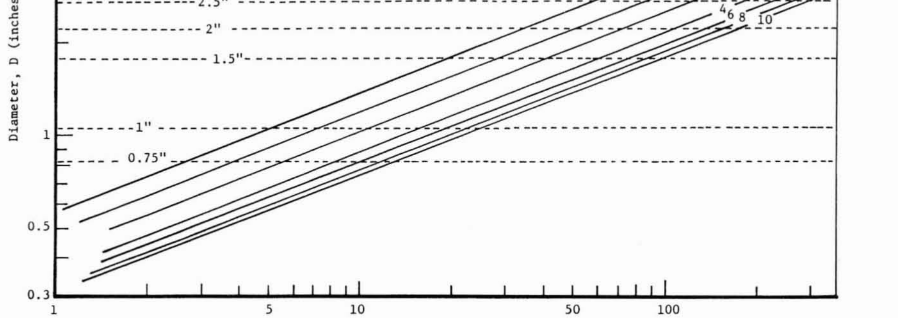



Figure 24. Submain design chart—slope larger than 5 percent.

variation along a submain is affected by friction drop only and the maximum energy drop (or pressure drop) is at the end of submain. Therefore, Equation 12 can be written as

$$\frac{\Delta H}{H} = 3.42 \times 10^{-4} \frac{Q^{1.852}}{D^{4.871}} \frac{L}{H} . \qquad \ldots (43)$$

By setting $\Delta H/H$ = 20 percent, which is the allowable pressure variation, Equation 43 becomes

$$0.20 = 3.42 \times 10^{-4} \frac{Q^{1.852}}{D^{4.871}} \frac{L}{H} . \qquad \ldots (44)$$

Equation 44 can be plotted as a simple design chart as shown in Figure 25, which can be used for submain design from the total discharge and a length and pressure head ratio $L/H$. The design procedure for using the simplified design charts, Figures 24 and 25, are as follows:

1. Determine the total discharge $Q$ for submain.
2. Determine the length and pressure ratio $L/H$.

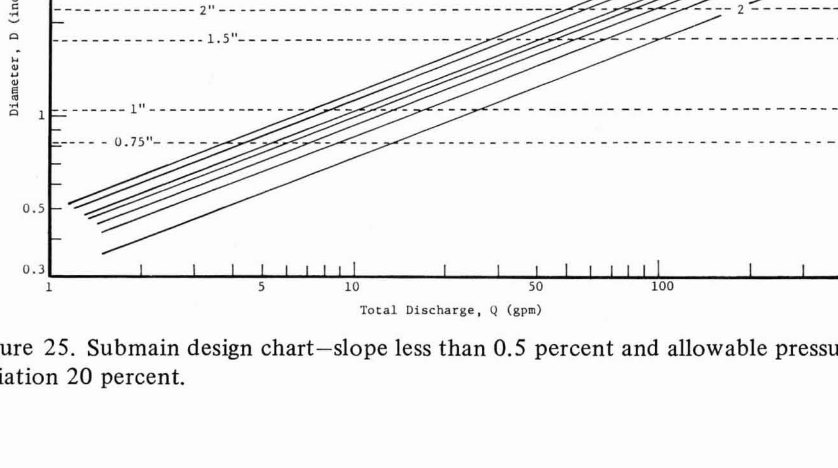



Figure 25. Submain design chart—slope less than 0.5 percent and allowable pressure variation 20 percent.

3. Determine the submain slope. If the submain slope is less than 0.5 percent, use Figure 25 to design the submain size.
4. If the submain slope is equal to or larger than 0.5 percent and equal or less than the maximum slope determined for the $L/H$ ratio in Figure 23, the submain size can be determined by using Figure 24.
5. If the submain slope is larger than the maximum slope (Figure 24) the simplified submain charts cannot be used. The design can be done by using the general submain design chart given earlier in which it may be necessary to adjust the design by using different submain length ($L$) or different water pressure ($H$).

## Submain Design for Irregular-Shaped Fields

The general submain design charts and the simplified submain design charts presented in the previous two sections were developed based on an assumption that the field is a rectangular shape. When the field shape is not rectangular but can be considered trapezoidal or triangular, adjustments can be made so the charts originally developed for rectangular fields can be used (*17*).

Since the total discharge is a big factor for submain design, the adjustment was made for the irregular-shaped fields so the adjusted total discharge can be used directly in the design charts for designing submain size. This was done by determining first the percentage of total discharge that can be used in Equation 6 to determine the total energy drop by friction, $\Delta H$, at the end of the submain. This can be expressed as

$$\Delta H = 9.76 \times 10^{-4} \frac{(CQ)^{1.852}}{D^{4.871}} L \qquad \ldots (45)$$

where $\Delta H$ is the total energy drop in feet, $L$ is the total submain length in feet, $Q$ is the total discharge at the inlet of submain in gpm, $D$ is the submain inside diameter in inches, and $C$ is a coefficient expressed in a percentage (less than 1) that has different values depending on the shape of the field. The $C$-value for a rectangular field is determined by equalling Equation 45 to Equation 12 and found to be 0.57.

Suppose the irregular shape of the fields can be considered as a trapezoid in two groups as shown in Figures 26 and 27. Group 1

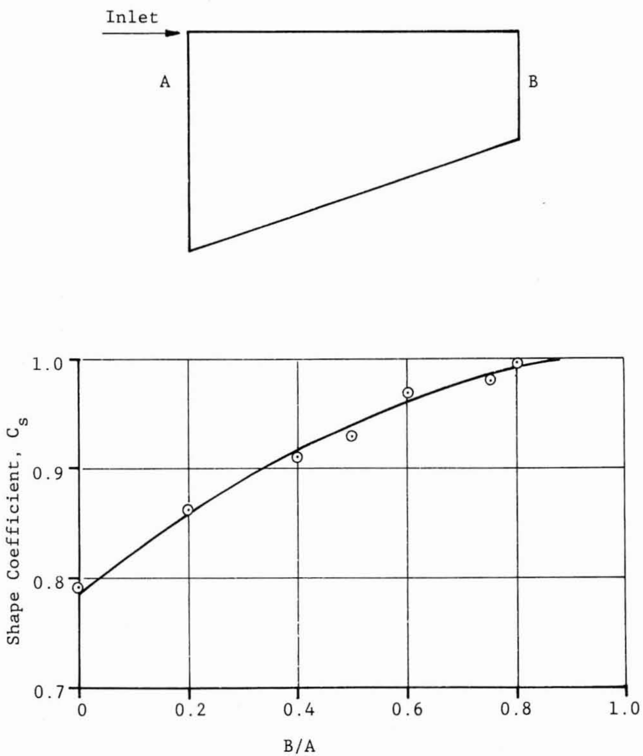



Figure 26. Field shape (Group 1) and the shape coefficient for submain sizing.

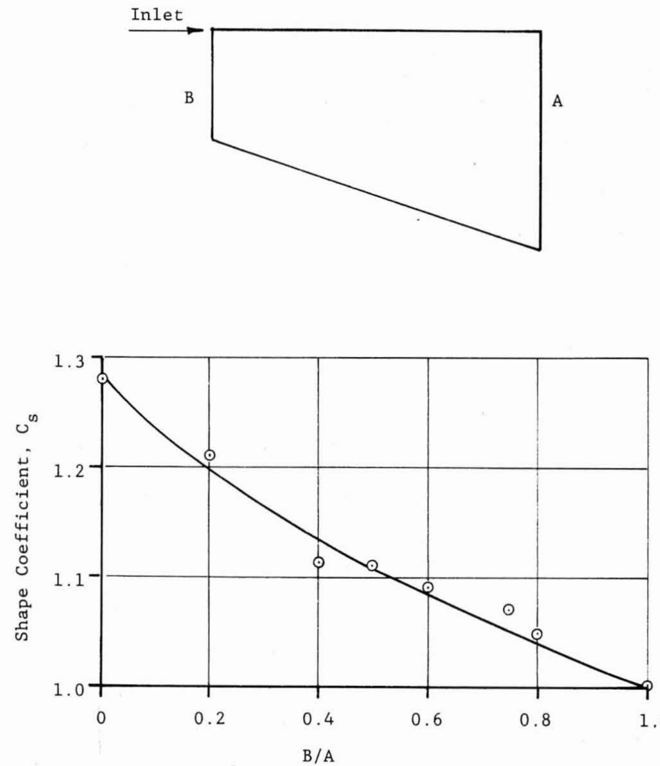



Figure 27. Field shape (Group 2) and the shape coefficient for submain sizing.

(Figure 26) shows the flow direction in the submain is from long lateral ($A$) to short lateral ($B$) and Group 2 (Figure 27) shows the reverse condition. When B is zero the field will be triangular. The different values of $B/A$ ratio represent the different trapezoidal shapes. A computer program was prepared to determine $C$-values for different field shapes (different $B/A$ values). Using an average situation that the total number of laterals is about 40 to 50, the $C$-values are found as follows:

1. Group 1–flow direction from $A$ to $B$ (Figure 26)

| $B/A$ | $C$ |
|---|---|
| 0 | 0.45 |
| 0.2 | 0.49 |
| 0.4 | 0.52 |
| 0.5 | 0.53 |
| 0.6 | 0.55 |
| 0.75 | 0.56 |
| 0.8 | 0.57 |
| 1.0 | 0.57 |

2. Group 2–flow direction from $B$ to $A$ (Figure 27)

| $B/A$ | $C$ |
|---|---|
| 0 | 0.73 |
| 0.2 | 0.69 |
| 0.4 | 0.65 |
| 0.5 | 0.64 |
| 0.6 | 0.62 |
| 0.75 | 0.61 |
| 0.8 | 0.60 |
| 1.0 | 0.57 |

This shows that when the ratio $B/A = 1$, the shape of the field is rectangular and the $C$-value is 0.57. For different shapes, the $C$-values are different. This means for a given total discharge, $Q$, the total friction drop, $\Delta H$, will be different depending on the shape of the field. If the total energy drop, $\Delta H$, is constant, the total discharge, $Q$, will be different. This makes it possible to use the design chart for a rectangular shape if an adjusted total discharge can be obtained. The adjusted total discharge will give the same total energy drop $\Delta H$ in the design chart for a rectangular shape as the total energy drop determined by total discharge in an irregular-shaped field. The adjusted total discharge can be determined by

$$Q_{\text{adj}} = C_s Q \qquad \ldots (46)$$

in which $Q_{\text{adj}}$ is the adjusted total discharge and $C_s$ is a shape coefficient which is determined by simply comparing the $C$-value of a given field shape to the $C$-value of a rectangular field. The shape coefficient, $C_s$, for different $B/A$ ratios were plotted and are shown in Figures 26 and 27. When the adjusted total discharge is obtained, the design charts, Figures 11, 12, 24, and 25, can be used for submain design.

For irregular-shaped fields the energy gradient pattern along the submain is different as shown in Figure 28. Figure 28 shows the dimensionless energy gradient lines for five different field shapes: I and V are triangular, II and IV are trapezoids, and III is rectangular. Since the different field shapes show different energy drop patterns, the

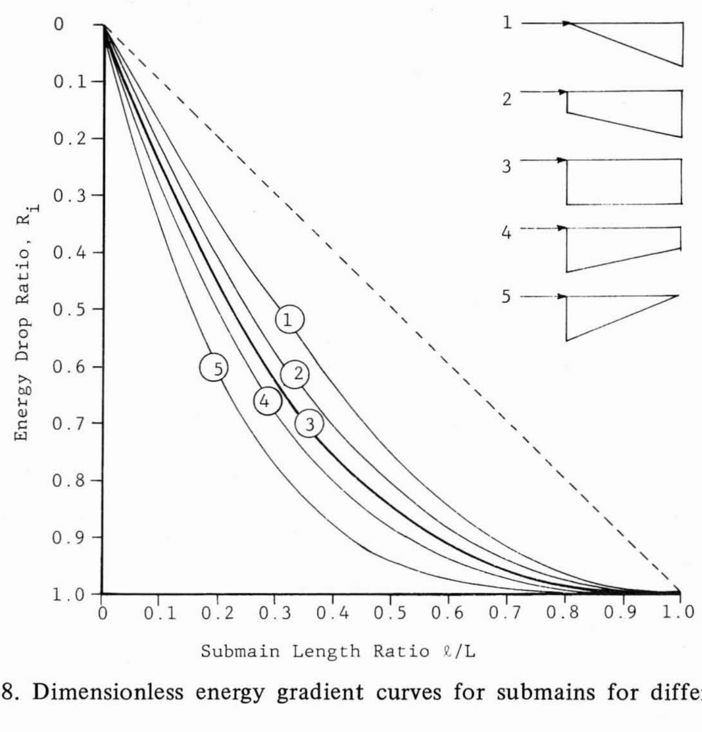



Figure 28. Dimensionless energy gradient curves for submains for different field shapes.

design charts in Figures 11 and 12 cannot be used unless the curves in the Quadrant I are determined based on the special field shape. However, for most trapezoid shapes when $B/A$ is larger than 0.5, the energy drop pattern is close to that of the rectangular shape; therefore, the design charts in Figures 11 and 12 can be used without causing much error.

The simplified design charts, Figures 24 and 25, can be used to design submains for irregular-shaped fields by using the adjusted total discharge. The design can be made by using Figure 24 for submain slopes equal or larger than 0.5 percent. The maximum slopes allowed in the design for different $L/H$ values for five different field shapes are shown in Figure 29. It is interesting to note, as shown in Figure 29, that

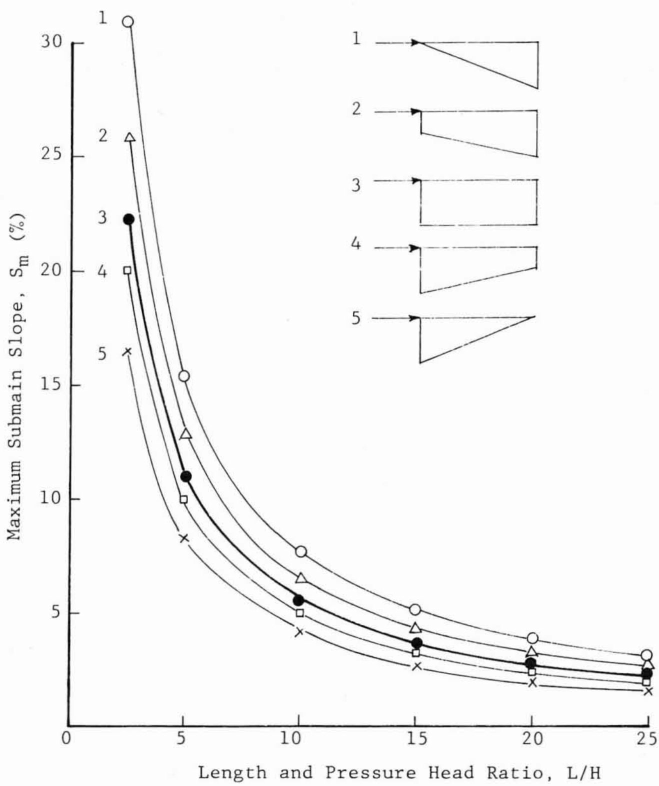



Figure 29. Maximum submain slope to maintain a 20 percent pressure variation when slope is used for submain design (simplified design chart, Figure 24).

the different field shapes will not greatly affect the maximum slope compared with the maximum slope for a rectangular situation. In general practice, it can be concluded that when $L/H$ is 5 or 10 the maximum slope of the submain can be between 5 and 10 percent. When the submain slope is less than 0.5 percent, Figure 25 can be used by simply applying the adjusted total discharge.

The design procedure listed below is for irregular-shaped fields using the general design charts in Figures 11 and 12 for submain design:

1. Determine the total discharge, $Q$.
2. From the field shape and the flow direction in the submain, identify the group (Group 1 or 2) and determine the values of $A$ and $B$.
3. Calculate $B/A$ and determine the shape coefficient $C_s$ from either Figure 26 (Group 1) or Figure 27 (Group 2).
4. Determine the adjusted total discharge from Equation 46.
5. Design the submain using Figures 11, 12, 13, and 14 and using the same design procedure as presented in the sections on general design charts.

The design procedure for irregular-shaped fields using the simplified design charts, Figures 24 and 25, for submain design is as follows:

1–4. Same as listed in the previous section for using the general design charts.

5. Calculate the length and head ratio, $L/H$.
6. Determine the submain slope.
7. If the submain slope is less than 0.5 percent, use $L/H$ and the adjusted total discharge, $Q_{adj}$, in Figure 25 to determine the submain size.
8. If the submain slope is equal or larger than 0.5 percent, check the slope with the maximum slope from Figure 29.
9. If the slope is less than the maximum slope, use the slope and the adjusted total discharge, $Q_{adj}$, in Figure 24 to design submain size.
10. If the slope is larger than the maximum slope, a smaller $L/H$ can be obtained by adjusting submain length or operating pressure, thus a maximum slope larger than the submain slope can be obtained (from Figure 29). Then Figure 24 can be used in designing the submain size.

### Design of Drip Irrigation Submains with Varying Pipe Sizes

Most of the drip irrigation submains are designed for a single size. However, under certain situations where the submain is relatively long and laid on nonuniform slopes or designed for high uniformity, the submain can be designed using varying sizes. The hydraulic analysis and design procedures are the same as those for laterals as presented in the section on the design chart for drip irrigation laterals with varying pipe sizes.

## DESIGN OF DRIP IRRIGATION MAIN LINES

The main line design (*9*) is based on the topographic condition, the operating pressure, the field layout of laterals and submains, and the required discharge from each outlet along the main line. The main line can be a single pipe that supplies water to a field (a submain). Main line design can be done by considering simply a pipe flow in which the pipe size can be determined by the allowable energy drop, $\Delta H$, and the main line length, $L$. When a main line system is supplying water to a series of fields, the main line flow capacity (discharge in the pipe) changes with respect to the length; it has more discharge in the upstream sections than in the downstream sections. In the main line design, it is necessary to select the proper pipe size for each section in order to deliver water at the required rate to all submains in the system at a pressure equal to or larger than the required pressure. There are numerous arrangements of pipe sizes that can be designed to meet the hydraulic situation of a given field layout, and there are many different layouts that can be made for a given field. Every different field layout and different arrangement of pipe sizes will indicate a different cost. The final goal of the main line design will be not only the optimal design within a given field layout but also the optimal design among several field layouts.

### The Energy Gradient Line

The main line design is a series of pipe flow designs. Once the field layout is set, the required discharge rate in each section can be determined. In common practice, the Williams and Hazen formula is

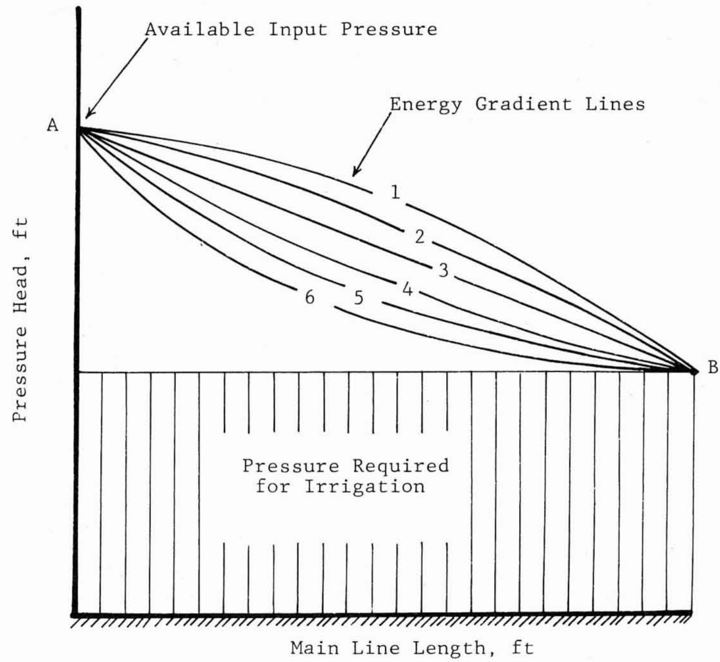



Figure 30. Main line profile and energy gradient lines.

used to determine pipe sizes; this formula for plastic pipe is given in Equation 6, which can be rearranged as

$$\frac{\Delta H}{\Delta L} = 9.76 \times 10^{-4} \frac{Q^{1.852}}{D^{4.871}} \qquad \ldots (47)$$

in which $\Delta H/\Delta L$ is the energy slope. Equation 47 shows that the pipe size, $D$, can be determined for a given discharge, $Q$, if the energy slope is known. This means that there are numerous solutions of pipe size, $D$, for different specified energy slopes for a given discharge, $Q$. The energy slope, or the slope of the energy gradient line, should be selected so that the energy gradient line is above the required water pressure along the main line as shown in Figure 30. The water pressure in the main line must always be equal to or higher than the required water pressure for drip irrigation operation along the main line.

## The Optimal Shape of the Energy Gradient Line

The energy gradient line can be a straight line or curves as shown in Figure 30. As long as the total energy is higher than the required water pressure, the design is hydraulically sound. Figure 30 shows the main line profile drawn for a nearly level topographic condition and a required water pressure along the line. If an available inlet pressure at point $A$ is determined, and point $B$ indicates the pressure required at the downstream point, a straight line and curves will connect $A$ and $B$ as shown in Figure 30. The straight energy gradient line $AB$ is one solution, and all the curves connecting $AB$ are other solutions. All solutions will give different costs for the main line system. It is necessary to determine an optimal energy gradient line (or curve) that will have the minimum cost.

The optimal shape of the energy gradient curve depends on the number of outlets and required discharge from each outlet, the number of sections, and the length of each section (*9*). Suppose a main line has 10 equal sections (each section has an equal length, $\Delta L$, which is 10 percent of the total length, $L$), and the outlet discharge, $q$, from each section is equal; the total cost of the main line will be

$$C = \Delta L \, (C_1 + C_2 + C_3 + \ldots + C_{10}) \qquad \ldots (48)$$

in which $C$ is the total cost; and $C_1, C_2, C_3, \ldots, C_{10}$ are the unit cost of pipe for sections 1, 2, 3, . . . , 10, respectively, counting from the downstream end. The unit pipe cost and its size can be expressed as a power function, which can be shown by plotting the pipe sizes and their unit costs on log-log paper. A straight line can be drawn on the log-log paper and expressed as

$$C = a D^b \qquad \ldots (49)$$

in which $a$ and $b$ are two power function constants; therefore, the cost of the main line can be expressed as

$$C = \Delta L \cdot a \cdot (D_1^{\,b} + D_2^{\,b} + \ldots + D_{10}^{\,b}) \, . \qquad \ldots (50)$$

The Williams and Hazen formula, Equation 47, can be expressed as

$$D^y = \frac{\alpha Q^x}{S_f} \qquad \ldots (51)$$

in which $x = 1.852$; $y = 4.871$; $\alpha = 9.76 \times 10^{-4}$; and $S_f$ = energy slope. Substituting Equation 51 into Equation 50 yields

$$C = \Delta L \, a \, \alpha^{b/y} \; [(\frac{Q^x{}_1}{S_{f1}})^{b/y} + (\frac{Q^x{}_2}{S_{f2}})^{b/y} + \ldots + (\frac{Q^x{}_{10}}{S_{f10}})^{b/y}] \; . \qquad \ldots (52)$$

If the outlet discharge, $q$, is equal for all sections, Equation 52 can be rearranged as

$$C = \Delta L^{1+(b/y)} \; a \, \alpha^{b/y} \; q^{bx/y} \; [(\frac{1^x}{\Delta H_1})^{b/y} + (\frac{2^x}{\Delta H_2})^{b/y} + \ldots + (\frac{10^x}{\Delta H_{10}})^{b/y}] \; . \qquad \ldots (53)$$

For a design problem where $\Delta L$ and $q$ are given, the total cost can be expressed as

$$C = K[(\frac{1^x}{\Delta H_1})^{b/y} + (\frac{2^x}{\Delta H_2})^{b/y} + \ldots + (\frac{10^x}{\Delta H_{10}})^{b/y}] \qquad \ldots (54)$$

in which $K = \Delta L^{1+(b/y)} \; a \, \alpha^{b/y} \; q^{bx/y}$ = constant; $\Delta H_1$, $\Delta H_2$, $\Delta H_3$, . . ., $\Delta H_{10}$ are the energy drop for section 1 to section 10, respectively. The energy drop can be expressed as a percentage of the total drop, $\Delta H$, so Equation 54 will be

$$C = K \; (\Delta H)^{-b/y} \; [(\frac{1^x}{p_1})^{b/y} + (\frac{2^x}{p_2})^{b/y} + \ldots + (\frac{10^x}{p_{10}})^{b/y}] \qquad \ldots (55)$$

in which $p_1 = \Delta H_1 / \Delta H$, $p_2 = \Delta H_2 / \Delta H$, . . . , $p_{10} = \Delta H_{10} / \Delta H$. The $p$-values ($p_1$, $p_2$, . . . , $p_{10}$) will show the energy drop pattern or the shape of the energy gradient curve. When all the $p$-values are equal, and their value is 0.1, the energy drop pattern is a straight line. For a given design problem as shown in Figure 30, the $K$-value and $\Delta H$ are given and are constant, so Equation 55 can be shown as

$$C = K_1 \Phi \qquad \ldots (56)$$

in which $K_1 = K(\Delta H)^{-b/y}$ = constant; and

$$\Phi = [(\frac{1^x}{p_1})^{b/y} + (\frac{2^x}{p_2})^{b/y} + \ldots + (\frac{10^x}{p_{10}})^{b/y}] \ . \qquad \ldots (57)$$

A minimum $C$-value can be obtained if the arrangement of $p$-values will give a minimum $\Phi$. Substituting $x$- and $y$-values and using $b = 1.96$ for the pipe class PVC 125, the $\Phi$-value can be expressed as

$$\Phi = (\frac{1^{1.852}}{p_1})^{0.40} + (\frac{2^{1.852}}{p_2})^{0.40} + \ldots + (\frac{10^{1.852}}{p_{10}})^{0.40} \ . \qquad \ldots (58)$$

A computer program was prepared for Equation 58 to calculate $\Phi$ for different combinations of $p$-values. By comparing the results an optimal shape for the energy gradient curve can be obtained. Fifteen energy gradient patterns were studied and the optimal shape was found to be the heavy dash line as shown in Figure 31. Figure 31 was plotted as a dimensionless form, a length ratio, $l/L$, against the energy drop ratio, $\Delta H_i/\Delta H$, where $\Delta H_i$ is the total energy drop at a given length ratio, $i$, ($i = 0.1, 0.2, 0.3, \ldots, 1.0$). Fifteen energy gradient patterns are numbered from 1 to 15 as shown in Figure 31, and number 8 is the pattern for a straight line. The optimal shape of the energy gradient line was found by comparing the costs of all 15 patterns. A term called "sag" at the middle section (0.5 $L$) was used to characterize the different energy gradient patterns. The "sag" was defined as the distance between the curve and the straight line (Figure 31) at the length ratio 0.5. For energy gradient patterns 1 to 7, the distances from the straight line are expressed as minus (–) sag; plus (+) sags are used for energy gradient patterns 9 to 15. The sag is a length unit and is expressed as a percentage of the total drop, $\Delta H$. The cost of different energy gradient patterns was compared with the cost of the straight energy gradient line and expressed as a term called "cost ratio." The

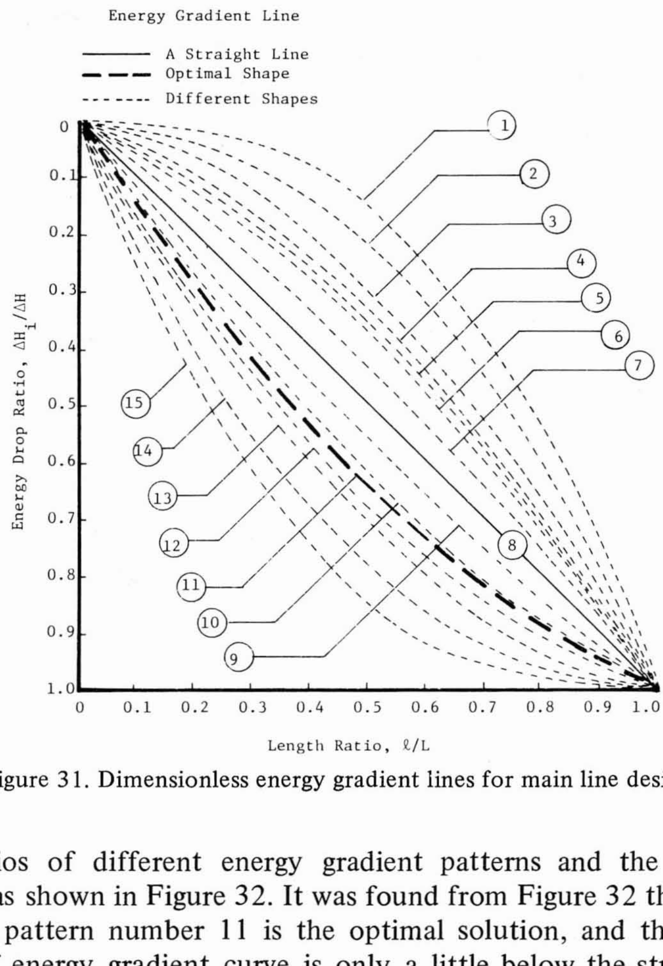



Figure 31. Dimensionless energy gradient lines for main line design.

cost ratios of different energy gradient patterns and the sag were plotted as shown in Figure 32. It was found from Figure 32 that energy gradient pattern number 11 is the optimal solution, and the optimal shape of energy gradient curve is only a little below the straight line with a sag around 0.15 $\Delta H$.

It also was found that by applying a dynamic program optimization (*5*) on nine arbitrary design examples (*9*) the optimal shape of the energy gradient curve is very close to the optimal shape determined by Equation 58.

## A Straight Energy Gradient Line

The analysis of the optimal shape of the energy gradient curve as shown in Figure 32 indicated that the difference in cost between the

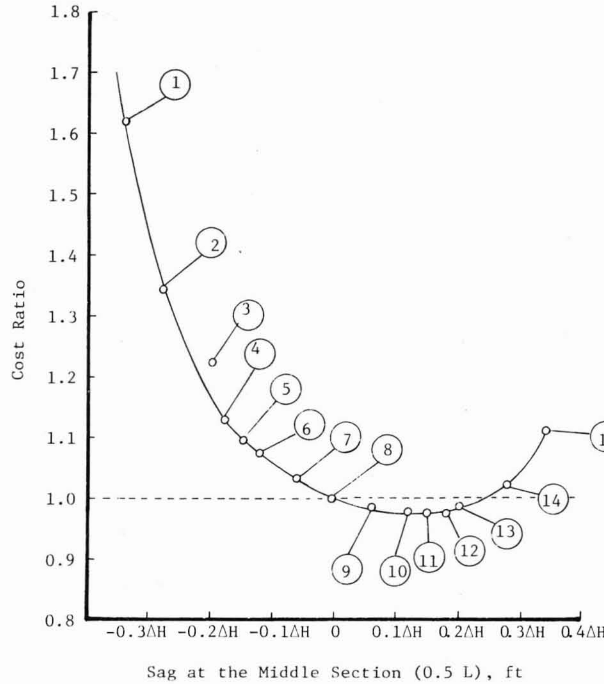



Figure 32. Cost evaluation of different energy gradient patterns.

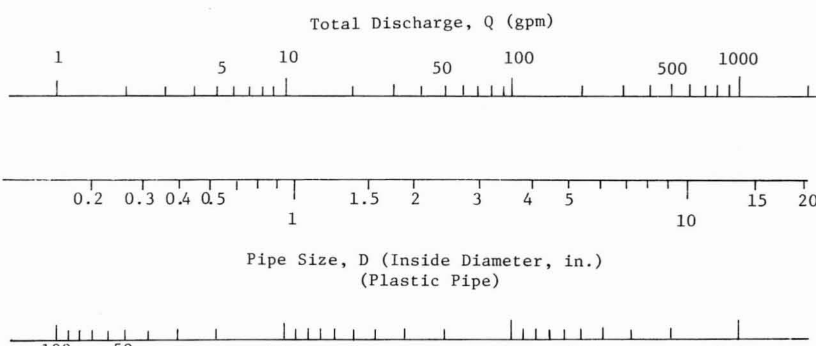
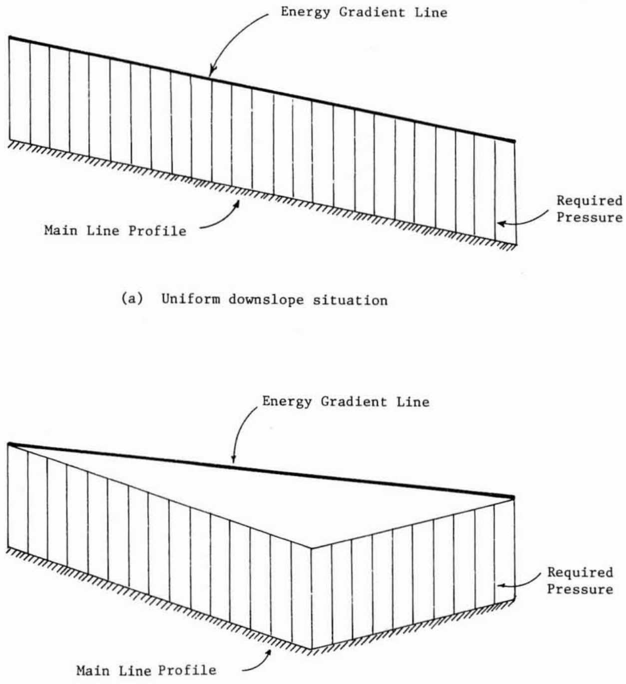


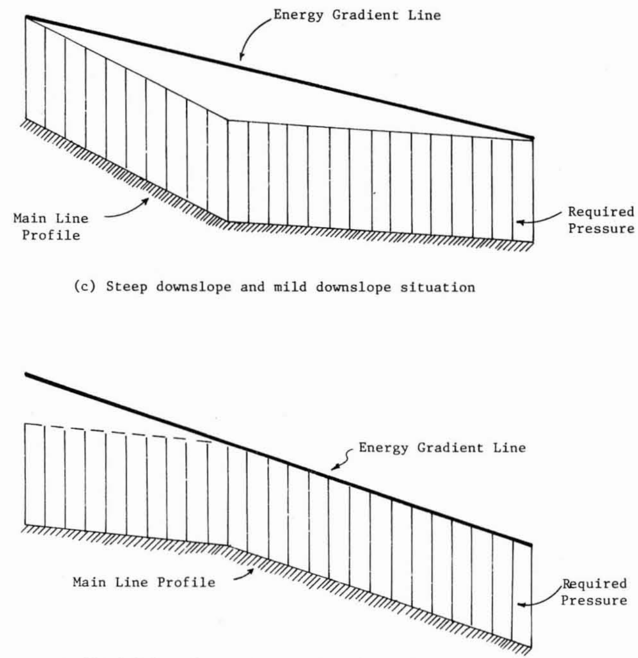

Figure 33. Nomograph for drip irrigation main line design in British units.
NOTE: Calculated by Williams and Hazen formula, $C = 150$.




(a) Uniform downslope situation

(b) Downslope and upslope situation

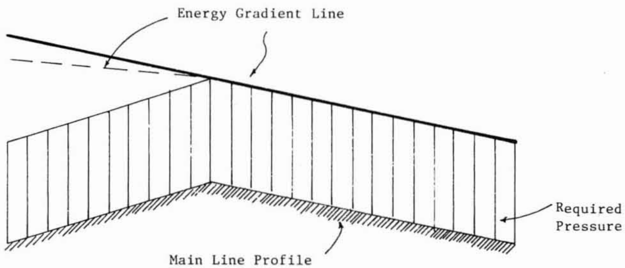
Figure 34. Energy gradient lines for different field situations, (a), (b).



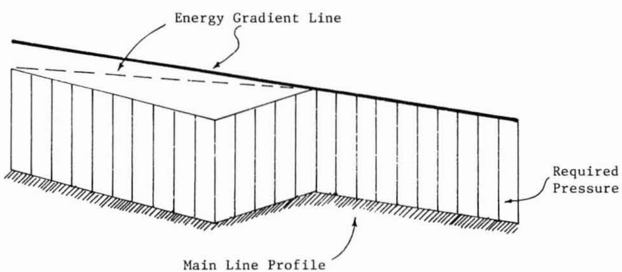

(c) Steep downslope and mild downslope situation

(d) Mild downslope and steep downslope situation

Figure 34. Energy gradient lines for different field situations, (c), (d).

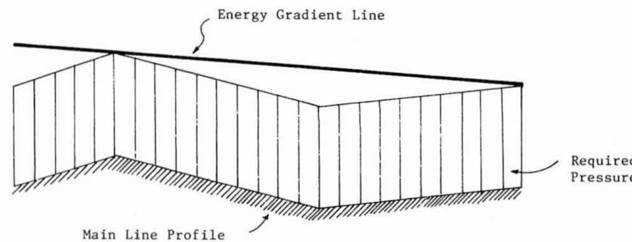



(e) Upslope and downslope situation

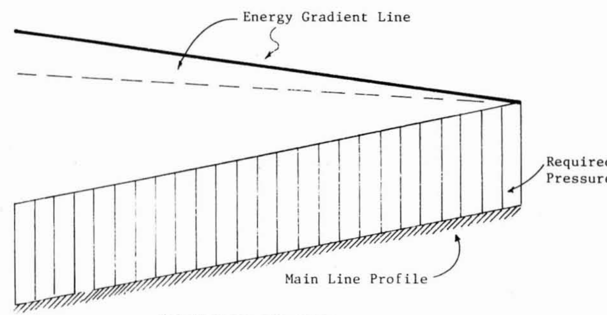



(f) Downslope, upslope, and downslope situation

Figure 34. Energy gradient lines for different field situations, (e), (f).




(g) Upslope, downslope, and upslope situation




(h) Upslope situation

Figure 34. Energy gradient lines for different field situations, (g), (h).

optimal shape and the straight line is only about 2 percent. This finding supplies a fast method of design, because a straight energy gradient line is easy to determine. If the main line profile, discharge, inlet pressure, and required pressure are known, the straight energy gradient line can immediately be determined. The design solution can be read directly from Figure 33 which is a plot of the Williams and Hazen formula as given in Equation 47. This technique can be applied especially to evaluate alternative field layouts. The design procedure is as follows:

1. Plot the main line slopes (profiles) and the required pressure for the drip irrigation operation as shown in Figure 34. Figure 34 shows eight main line layouts on different topographic situations.
2. Plot the straight energy gradient line as suggested in Figure 34. If a higher inlet pressure (energy) is available, a steeper straight line can be used.
3. Determine the energy slope (the slope of the straight energy gradient line).
4. Determine the required discharge in each main line section.
5. Design the main line size by using Figure 33.

The nomograph shown in Figure 33 can be made as a slide rule and would be more convenient to use.

## DRIP IRRIGATION EFFICIENCY

The design of a drip irrigation system is based on the hydraulics of pipe flow. There are two irrigation efficiency terms: distribution and application. Distribution efficiency determines how uniformly irrigation water can be distributed through a drip irrigation system into the field. Application efficiency shows how well irrigation water is applied; that is, what percentage of water applied is stored in the root zone as required and available for plant use. The distribution efficiency can be determined from the emitter flow variation along a lateral line (or submain) of a field drip irrigation system and can be expressed by the equation

$$E_d = 100\left(1 - \frac{\overline{\Delta q}}{\bar{q}}\right) \qquad \ldots (59)$$

in which $E_d$ is the distribution efficiency (or uniformity coefficient), $\overline{q}$ is the mean emitter flow rate (or mean submain flow rate into its laterals), and $\overline{\Delta q}$ is the average absolute deviation of each emitter flow from the average emitter flow (or average absolute deviation of each lateral flow from the average lateral flow from a submain).

The application efficiency is defined as the ratio of water required in the root zone to the total amount of water applied. The water required in the root zone is assumed to be applied at the minimum flow rate and over the total irrigation time. Therefore, application efficiency can be expressed as

$$E_a = \frac{N q_{\text{min}} T}{\mathcal{V}} \qquad \ldots (60)$$

in which $E_a$ is the application efficiency, $N$ is the total number of emitters, $q_{\text{min}}$ is the minimum emitter flow rate, $T$ is the total irrigation time, and $\mathcal{V}$ is the total amount of water applied. Since the mean emitter flow is

$$\overline{q} = \frac{\mathcal{V}}{NT}, \qquad \ldots (61)$$

the application efficiency can also be expressed as

$$E_a = \frac{q_{\text{min}}}{\overline{q}}. \qquad \ldots (62)$$

## Emitter Flow Profiles

The distribution efficiency and application efficiency depend on the variation of emitter (or orifice) flow along the lateral line and the variation of the amount of flow from the submain into the laterals. The submain is usually short and can be designed to supply uniform amounts of flow to laterals. The distribution and application efficiencies are caused essentially by the flow variation along the lateral line. The emitter flow variation along a lateral is controlled by the pressure variations along a lateral line. Therefore, according to the pressure variations there are three different emitter flow profiles showing the emitter flow variation along a lateral line as shown in Figure 35. They are as follows:

Profile 1—Emitter flow decreases with respect to the lateral length. This profile occurs when the lateral is laid on zero or uphill slopes. In this condition, $q_{max}$ is determined by the input (operating) pressure.

Profile 2—Emitter flow decreases with respect to the lateral length and reaches a minimum emitter flow point and then increases with respect to further length of lateral line. This occurs when a gain of energy by slopes at downstream points is larger than the energy drop by friction. This type usually occurs when the lateral line is

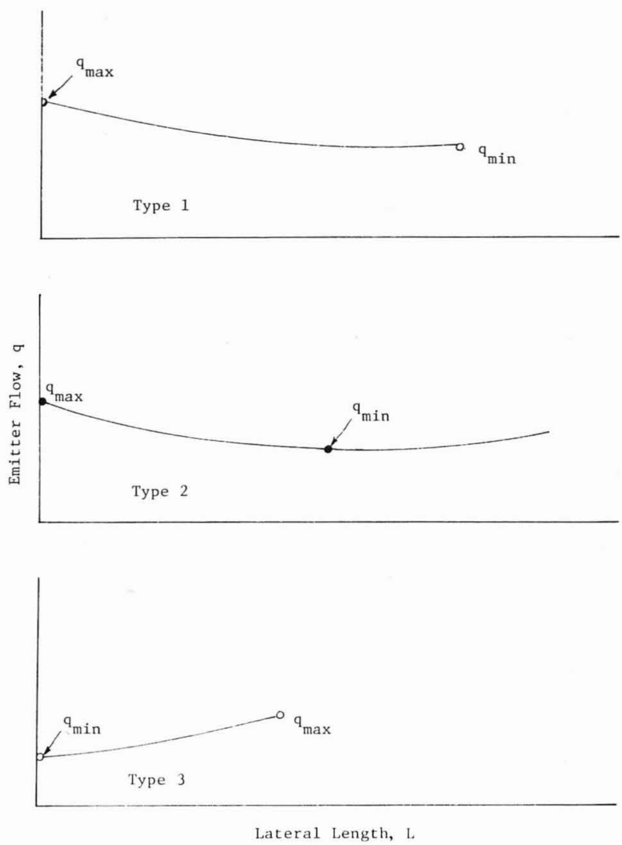



Figure 35. Emitter flow profiles along a lateral line.

laid on mild downhill slopes. In this condition, $q_{max}$ is determined by the input pressure.

Profile 3–Emitter flow increases with respect to the lateral length. This is caused by steep downslopes where the energy gain is larger than the friction losses for all sections along the lateral line. In this condition, $q_{min}$ is determined by the input pressure.

## Distribution Efficiency of Drip Irrigation

Distribution efficiency is relatively high for drip irrigation because water distribution is under full control. Drip irrigation can be controlled to achieve uniform irrigation (*4, 6*) that is nearly 100 percent distribution efficient. In common practice, a single type of lateral line (or emitter) is used, and the emitter flow variations along a lateral line are caused by the energy relation in the lateral line. The emitter flow variations can be shown as three emitter flow profiles as

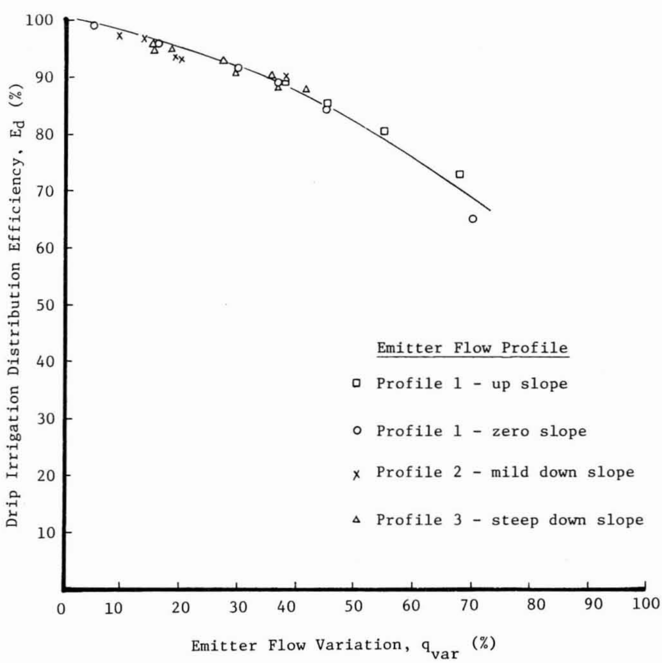



Figure 36. Relationship between drip irrigation distribution efficiency and emitter flow variation.

indicated in the previous section. A computer program (*10*) was developed to determine emitter flow profiles for a wide range of possible combinations of energy drop by friction and energy gain or loss by slopes. The distribution efficiency (or uniformity coefficient) for each profile can be determined. The emitter flow variation as defined in Equation 29 also can be determined from the computer program. The relationship between the distribution efficiency and emitter flow variation for all three emitter flow profiles was determined as shown in Figure 36. Figure 36 shows that if the emitter flow variation is designed for less than 20 percent, the distribution efficiency is always larger than 95 percent.

## Application Efficiency of Drip Irrigation

The application efficiency of a drip irrigation lateral can be determined from Equation 62 considering that the minimum emitter

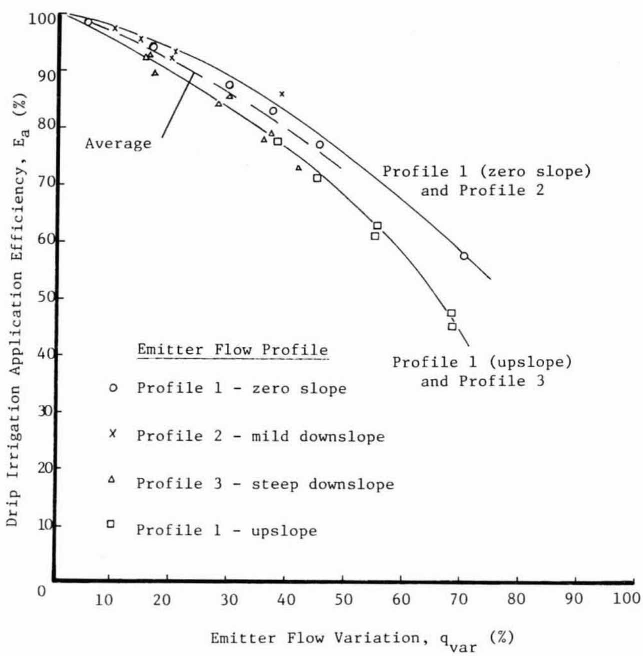



Figure 37. Relationship between drip irrigation application efficiency and emitter flow variation.

flow rate, $q_{min}$, and the irrigation time meet the water requirement. A computer simulation program (*10*) was developed to determine emitter flow profiles for a wide range of possible combinations of friction drop and energy gain or loss by slopes. The average emitter flow and minimum emitter flow can be calculated to determine the application efficiency. The application efficiency and emitter flow variations are plotted as shown in Figure 37. Two curves were plotted in Figure 37—one for emitter flow profiles 1 and 2 (zero slope and mild downslope) situations, and the other for emitter flow profile 3 (steep downslope) and profile 1 (upslope) situations. The difference between the two curves is small for small emitter flow variations. An average curve can be plotted to show the relationship between application efficiency and emitter flow variation of less than 40 percent. This average curve is plotted as a dash line in Figure 37.

It is interesting to note that if the design criterion is set to have an emitter flow variation of less than 20 percent, the application efficiency is larger than 90 percent, which is difficult to achieve in any other type of irrigation system.

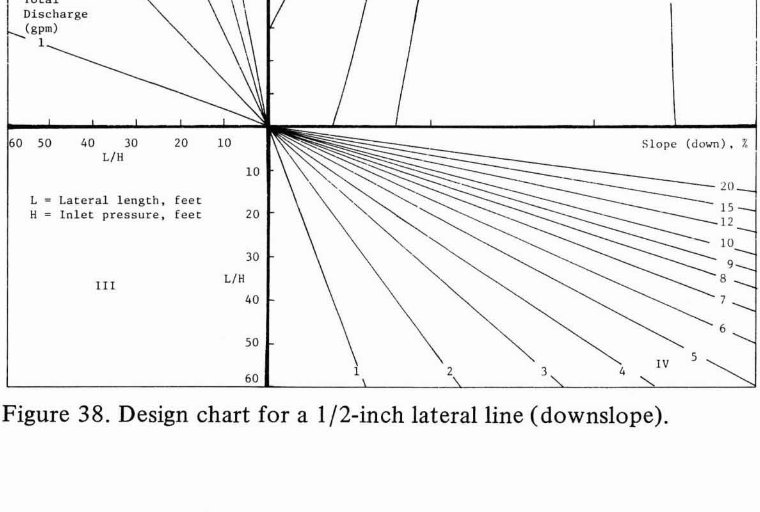



Figure 38. Design chart for a 1/2-inch lateral line (downslope).

## Design Criterion for a Drip Irrigation System

There is no definite rule about the design criterion for drip irrigation. Most designers are using an emitter flow variation of 10 percent (*2*) as a design criterion for a lateral line. If a submain is also designed for 10 percent lateral flow variation, then the emitter variation for a whole field is 20 percent. This will give an application efficiency of 90 percent for the whole field. When submain is designed with less than 10 percent lateral flow variation, the application efficiency of the whole field will be larger than 90 percent. In case the lateral line is designed for a 20 percent emitter flow variation and a submain is designed for a 10 percent lateral flow variation, the overall irrigation application efficiency still will be about 85 percent.

The design charts developed for lateral lines and submains as shown in Figures 7, 8, 11, and 12 can be plotted using application efficiency as the design criterion (in Quadrant I). A set of design charts for a 1/2-inch lateral line using irrigation application efficiency as the design criterion is plotted and shown in Figures 38 and 39.

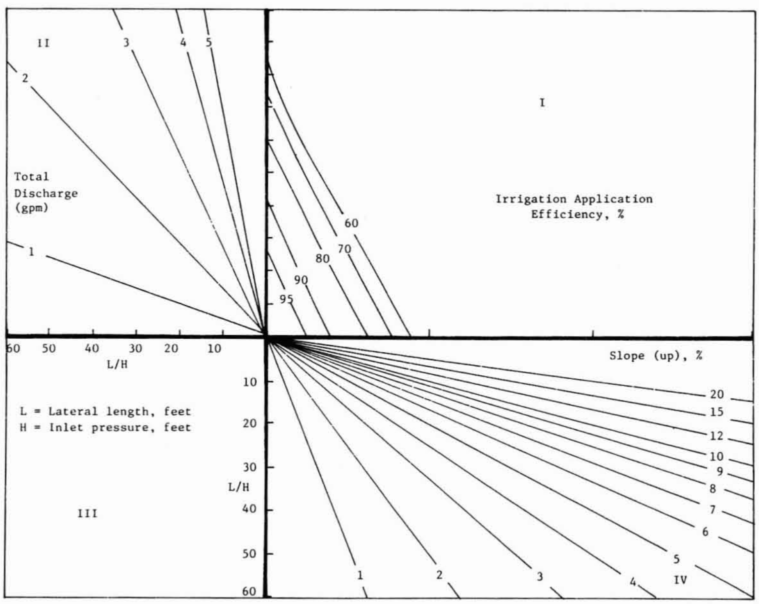



Figure 39. Design chart for a 1/2-inch lateral line (upslope).

## DESIGN OF A DRIP IRRIGATION SYSTEM

A drip irrigation system should be designed to meet the water requirement of the crop and the availability of water resources. The irrigation schedule should be designed to maintain the ideal soil moisture level in the root zone for the crop. The system must be hydraulically sound and must achieve the uniformity desired.

### Design Capacity

The design capacity is defined as a flow rate per unit area, usually expressed as gallons per minute per acre (gpm/acre). It is determined by the water requirement, irrigation time, and irrigation application efficiency. It can be expressed as

$$Q_c = \frac{450\,d}{T\,E_a} \qquad \ldots (63)$$

in which $Q_c$ is the design capacity, in gpm/acre; $T$ is the irrigation time, in hours; $d$ is the irrigation application, in inches; and $E_a$ is the irrigation application efficiency. The irrigation application, $d$, can be determined by

$$d = C_u\,I \qquad \ldots (64)$$

in which $C_u$ is the consumptive use, in inches per day, and $I$ is the irrigation interval, in days. The design capacity also indicates the acreage that can be irrigated by the available water resource.

Equations 63 and 64 consider that the whole area is irrigated; this is probably true for row crops. For orchards where only portions of the area are irrigated, a percentage of the total area should be used. For these situations, Equation 63 can be revised to

$$Q_c = \frac{450\,pd}{T\,E_a} \qquad \ldots (65)$$

where $p$ is a portion of area, sometimes defined as area covered by crops, and expressed as a percentage. It is also called the coverage factor. The coverage factor is usually assumed to be 1 for vegetables.

The irrigation engineer must first determine the irrigation application, in inches, from consumptive use (water requirement) and irrigation interval. This depends on the crop and soil conditions. When the required irrigation application is determined, the next consideration is the irrigation time, that is how long does it take to distribute the water into the field. The irrigation time will be determined based on the soil's intake rate, availability of labor, and time preferred by the irrigation engineer or farmer.

The design capacity can be calculated from Equation 63 or from Figure 40. Figure 40 is plotted from Equation 63 assuming the irrigation application efficiency is 1 (100 percent). The design capacity obtained from Figure 40 can be adjusted for different irrigation application efficiencies depending on the designed drip irrigation system.

The design capacity determined by Equation 63 is the flow rate (capacity) for a unit area (1 acre). It can be shown as a specific design capacity for drip laterals as follows

$$Q_{100} = \frac{S}{435.6} Q_c \qquad \ldots (66)$$

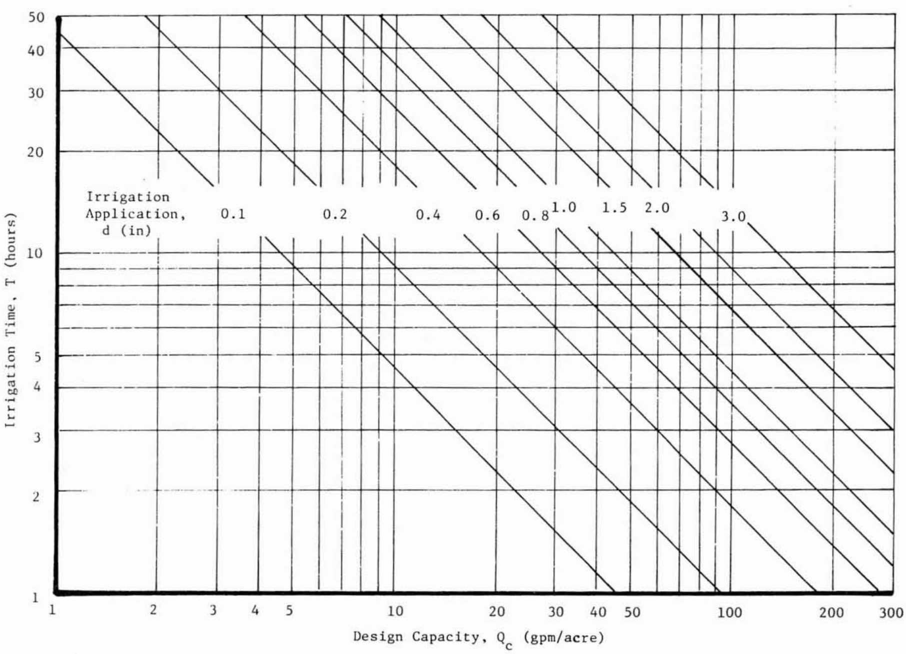



Figure 40. Determination of design capacity.

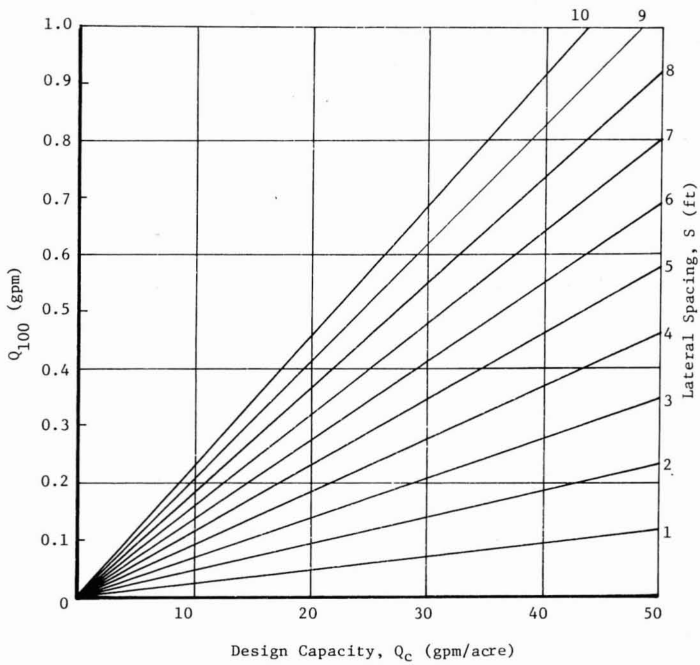



Figure 41. Selection of $Q_{100}$ from lateral spacing and design capacity.

in which $Q_{100}$ is the specific design capacity for drip irrigation laterals, expressed as gpm/100 feet of drip irrigation lateral line, and $S$ is the spacing of drip laterals, in feet. The specific design capacity, $Q_{100}$, can be used for selecting drip irrigation laterals or the operating pressure. Equation 66 can be plotted as a design chart for specific design capacity, $Q_{100}$, as shown in Figure 41.

## Selection and Design of Lateral Lines

When the design capacity, $Q_c$, is determined, the specific design capacity for a lateral line, $Q_{100}$, can be calculated using Equation 66 or determined from Figure 41 for a given selected lateral spacing, $S$. The specific design capacity, $Q_{100}$, is used for selecting the lateral line type. A specific type of lateral line (or certain emitters) will be selected to match the specific design capacity, $Q_{100}$, with the operating pressure that is available in the field. The lateral line length can now be designed based on the field slope (uniform or nonuniform), a lateral line size, and the design criterion. The design charts and procedures presented in the sections on lateral line design can be applied.

## Field Layout and the Design of Submains and Main Lines

With the selection of a lateral line and the design length (maximum allowable length) of the lateral, a general layout of the drip irrigation system can be made on the topographic map. Location of submains can be designed. The subfield controlled by each submain is commonly designed around one or two areas. The size of submain can be designed based on the area of the subfield and the design capacity. The general design charts, simplified design charts, and procedures for submain design presented earlier can be used. The main line design can be done by using the straight energy gradient line concept. The total discharge in each main line section is determined from the water requirement of the submains (or subfields). It also is necessary to design for several alternative layouts and select the least costly design. Here are a few guidelines for a field layout of a drip irrigation system:

1. Take advantage of the land slope.
2. Irrigate both sides of the main line.
3. Make the layout as simple as possible.
4. The size of the subfield should be 1–2 acres.

## Design Examples

Several design examples are given here to show the use of the developed design charts in drip irrigation design (*19*):

I. Lateral Line Design on Uniform Slope

*Design Example 1*

The operating pressure of a lateral line is 6.5 psi (15 ft), the length of lateral line is 300 ft, the total discharge is 2 gpm, the lateral line slope is 2 percent (downslope) and the lateral line size is 1/2-inch (0.625-inch I.D.). Check the acceptability of the design.

The solution can be read from Figures 7 and 9 by the following procedure:

a. Calculate $L/H = 20$.
b. From Figure 7 (or Figure 9) in Quadrant III, move vertically from $L/H = 20$ to the total discharge line ($Q$ = 2gpm); then establish a horizontal line into Quadrant I.
c. Move horizontally from $L/H = 20$ in Quadrant III to the 2 percent downslope line in Quadrant IV; then establish a vertical line into Quadrant I.
d. The intersection point of the two lines in Quadrant I shows a uniformity coefficient $C_u$ = 97 percent (emitter flow variation = 13 percent). The design is accepted.

*Design Example 2*

A lateral line length in a vegetable field is 150 ft and the slope of lateral line is 1 percent downslope. Emitters spaced 1 ft apart are installed in the lateral line. The emitter flow is 1 gph at an operating pressure of 15 psi. Design the lateral line size.

Given information:

Lateral length $L$ = 150 ft
Operating pressure $H$ = 15 psi = 34 ft
Number of emitters = 150 ·
Total discharge $Q$ = 150 gph = 2.5 gpm

Design procedure:

a. Calculate $L/H = 150/34 = 4.4$.
b. From Figure 11 and using the desirable zone (zone A) as the design criterion, a $\Delta H/L$ value is determined as 6.
c. From the nomograph, Figure 13, using the total discharge, $Q$ = 2.5 gpm, and $\Delta H/L = 6$, the minimum lateral size is determined as 0.5-inch (I.D.).

II. Lateral Line Design on Nonuniform Slopes

*Design Example 3*

A 400-ft, 1/2-inch lateral line is laid on a nonuniform slope. The nonuniform situation can be expressed as follows:

| | |
|---|---|
| 0–100 ft | 3% down |
| 100–200 ft | 2% down |
| 200–300 ft | 0% down |
| 300–400 ft | 3% down |

The operating pressure for drip irrigation is 15 psi, and the total discharge for the lateral line (400 ft long) is 2 gpm. Suppose the total energy drop by friction is determined as 5 ft. Check the pressure variation.

Given information:

$H = 34$ ft
$L = 400$ ft
$\Delta H = 5$ ft

Solution:

a. Determine

$$L/H = \frac{400}{34} = 11.76$$

and

$$\Delta H/H = \frac{5}{34} = 0.147.$$

b. Nonuniform slopes

| $l/L$ | $\Delta H_i'$ (ft) | $\Delta H_i'/L$ |
|---|---|---|
| 0.25 | 3 | 0.0075 |
| 0.50 | 5 | 0.0125 |
| 0.75 | 5 | 0.0125 |
| 1.00 | 8 | 0.02 |

Plot $l/L$ versus $H_i'/L$ in Quadrant I.

c. Follow the procedure given in the previous section on design charts for laterals on nonuniform slopes to check the pressure variation from the operating pressure for four points at the length ratio 0.25, 0.50, 0.75, and 1.0, respectively. Results are shown in Figure 42. It is found in Quadrant III that the pressure variation along the lateral line is less than 10 percent. The design is accepted.

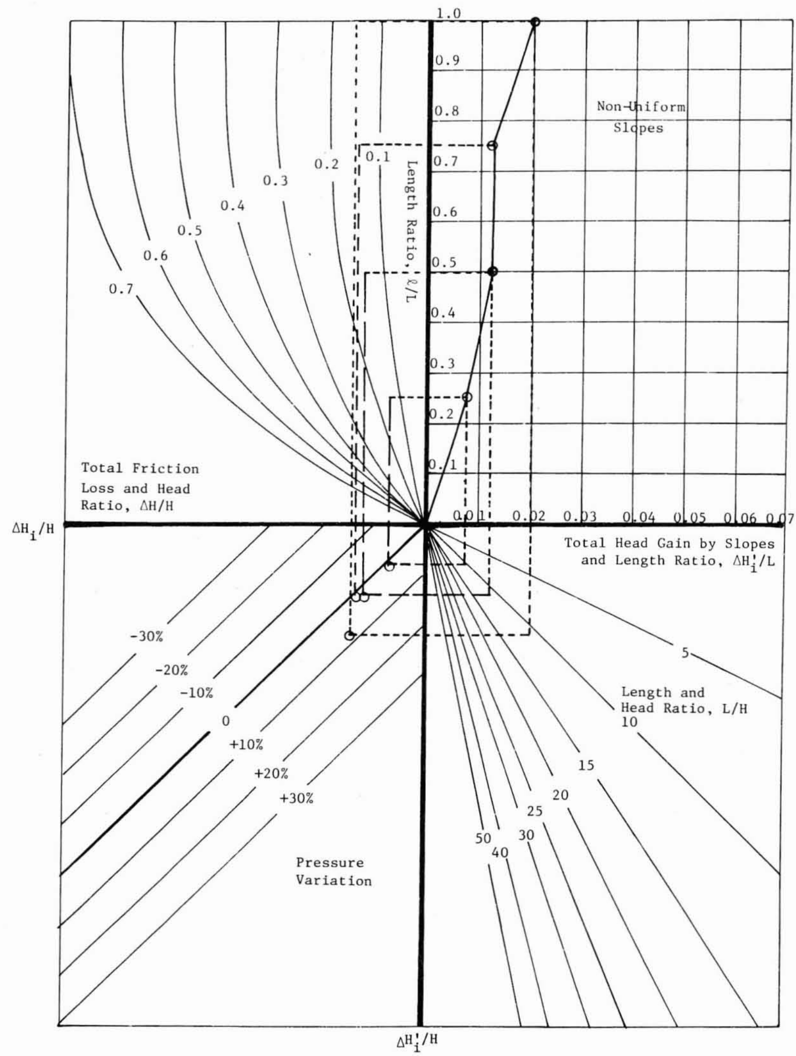



Figure 42. Design chart for nonuniform slopes (with a design example).

## III. Lateral Line Design with Varying Pipe Sizes

*Design Example 4*

In a papaya field the lateral line is 1000 ft long and laid on a uniform 5 percent downslope. The lateral line is designed to irrigate two rows of papaya. The papaya tree spacing is 5 ft in the row and the two rows are in an offset position. This means there is a papaya tree every 2.5 feet along the line. Microtubing is connected from the lateral line for irrigation and it is expected that each microtube will deliver 2 gph (gallons per hour) for irrigation under an operating pressure of 10 psi (23 ft). Design the lateral line size when different pipe sizes can be used along the lateral.

Design procedure:

a. Calculate total discharge $Q = 13.33$ gpm.
b. Lateral line slope: 5 percent (down).
c. If the lateral line is divided into 10 sections, the lateral size can be determined from Figure 19.

| Section | Mean discharge (gpm) | Lateral line size (inches) |
|---|---|---|
| 1 | 12.67 | 1¼ |
| 2 | 11.33 | 1¼ |
| 3 | 10.00 | 1 |
| 4 | 8.67 | 1 |
| 5 | 7.33 | 1 |
| 6 | 6.00 | 1 |
| 7 | 4.67 | ¾ |
| 8 | 3.33 | ¾ |
| 9 | 2.00 | ½ |
| 10 | 0.67 | ½ |

*Design Example 5*

The lateral line in Design Example 4 is laid on a nonuniform slope (down) as follows:

| | |
|---|---|
| 0–200 ft | 5% |
| 200–400 ft | 3% |
| 400–600 ft | 1% |
| 600–800 ft | 3% |
| 800–1000 ft | 5% |

Design the lateral line size.

Design procedure:

a. Calculate the total discharge $Q = 13.33$ gpm.
b. Lateral line slope: nonuniform.

c. If the lateral line is divided into 10 sections, the lateral size can be determined from Figure 19.

| Section | Mean discharge (gpm) | Slope (%) | Lateral line size (inches) |
|---|---|---|---|
| 1 | 12.67 | 5 | 1¼ |
| 2 | 11.33 | 5 | 1¼ |
| 3 | 10.00 | 3 | 1¼ |
| 4 | 8.67 | 3 | 1¼ |
| 5 | 7.33 | 1 | 1¼ |
| 6 | 6.00 | 1 | 1¼ |
| 7 | 4.67 | 3 | 1 |
| 8 | 3.33 | 3 | ¾ |
| 9 | 2.00 | 5 | ¾ |
| 10 | 0.67 | 5 | ½ |

IV. Submain Design Using a Single Size

*Design Example 6*

A subplot of a sugarcane field is a rectangular shape of 1 acre. The submain length is 100 ft and on a zero slope. The total discharge required for the submain to deliver is 15 gpm and the operating pressure is 15 psi (34 ft). Design the submain size.

Design procedure:

a. Total discharge $Q = 15$ gpm.

b. Calculate the submain length and pressure head ratio

$$L/H = 100/34 \cong 3.$$

c. Submain slope: 0 (zero).

d. From Figure 11 (using procedures described previously for the general design chart), $\Delta H/L$ is found to be 10 percent (pressure variation 20 percent) and from Figure 13, the pipe size is designed as 1 inch.

e. This design can also be made by using the simplified design chart, Figure 25, the submain can be read and designed as 1 inch.

*Design Example 7*

Use the same field as given in Example 6; the only difference is that the submain slope is 5 percent (down). Design the submain size.

Design procedure:

a. Total discharge $Q$ = 15 gpm.

b. Calculate the submain length and pressure head ratio

$$L/H = 100/34 \cong 3.$$

c. Submain slope: 5 percent (down)

d. From Figure 23 it is found that the maximum slope for $L/H = 3$ is 18 percent. The submain slope is less than 18 percent, so Figure 24 can be used. From Figure 24, submain size is designed as 1 inch.

*Design Example 8*

Suppose this 1-acre sugarcane field is in a trapezoidal shape. (Group 1 as shown in Figure 26) with $A$ = 150 ft and $B$ = 68 ft. The submain slope is 5 percent (down) and all other information is the same as given in Example 6.

Design procedure:

a. Total discharge $Q$ = 15 gpm.

b. Field shape Group 1; $A$ = 150 ft, $B$ = 68 ft (see Figure 26).

c. Calculate $B/A$ = 0.45. From Figure 26, the shape coefficient, $C_s = 0.93$.

d. Calculate the adjusted total discharge

$$Q_{\mathrm{adj}} = 0.93 \times 15 = 13.95 \text{ gpm}.$$

e. Calculate $L/H = 100/34 \cong 3$.

f. Submain slope: 5 percent (down).

g. From Figure 29 using shape IV the maximum slope for $L/H = 3$ is 16.5 percent which is larger than 5 percent submain slope.

h. Using Figure 24 for submain design:

$Q_{\mathrm{adj}}$ = 13.95 gpm
Slope = 5 percent (down)
Design submain size = 1 inch

V. Submain Design with Varying Pipe Sizes

*Design Example 9*

In a sugarcane field a submain is designed to control a 2-acre subfield. The field is a rectangular shape and the submain is 300 ft long. The total discharge required to irrigate the 2-acre field is 40 gpm. The submain slope is 3 percent (down). Design the submain size when different pipe sizes can be used for the submain.

Design procedure:

a. Total discharge $Q = 40$ gpm.
b. Slope: 3 percent downslope (uniform).
c. If the submain is divided into 10 sections, the submain size for each section can be determined from Figure 19.

| Section | Mean discharge (gpm) | Submain size (inches) |
|---|---|---|
| 1 | 38 | 2 |
| 2 | 34 | 2 |
| 3 | 30 | 2 |
| 4 | 26 | 1½ |
| 5 | 22 | 1½ |
| 6 | 18 | 1½ |
| 7 | 14 | 1¼ |
| 8 | 10 | 1¼ |
| 9 | 6 | 1 |
| 10 | 2 | ¾ |

## VI. Main Line Design

*Design Example 10*

A drip irrigation system is designed for a 50-acre papaya field. The area is rectangular and divided into 1-acre subplots that are irrigated by a submain from the main line. The main line is laid in the center of the field with 25 acres on both sides of the main line. Each subplot is about 435 ft long and 100 ft wide; each main line section is 100 ft long. The design capacity is 30 gpm per acre. There is a total of 24 sections and at the end of each section there will be an outlet to supply 60 gpm for irrigating both sides. If the main line slopes are plotted as shown in Figure 43 and the required water pressure for lateral line is 10 psi, design the main line.

Design procedure:

a. Plot the main line slopes (profiles) as shown in Figure 43.
b. Plot the required pressure, 10 psi, along the main line as 23 ft above the ground profile.

c. Determine the energy slope after plotting the input pressure and drawing the energy gradient line. From Figure 43, the energy slope is determined as 1 percent.

d. Design main line sizes. The main line sizes can be determined from the design chart, Figure 33, using a 1 percent energy gradient line. The results are as follows:

| Main line section | Discharge (gpm) | Design diameter (inches) |
|---|---|---|
| 0* | 1500 | – |
| 1 | 1440 | 10 |
| 2 | 1380 | 10 |
| 3 | 1320 | 10 |
| 4 | 1260 | 8 |
| 5 | 1200 | 8 |
| 6 | 1140 | 8 |
| 7 | 1080 | 8 |
| 8 | 1020 | 8 |
| 9 | 960 | 8 |
| 10 | 900 | 8 |
| 11 | 840 | 8 |
| 12 | 780 | 8 |
| 13 | 720 | 8 |
| 14 | 660 | 8 |
| 15 | 600 | 6 |
| 16 | 540 | 6 |
| 17 | 480 | 6 |
| 18 | 420 | 6 |
| 19 | 360 | 6 |
| 20 | 300 | 5 |
| 21 | 240 | 5 |
| 22 | 180 | 4 |
| 23 | 120 | 4 |
| 24 | 60 | 3 |

*There is an outlet at the entrance of section 1 for irrigating the subfields on both sides of section 1.

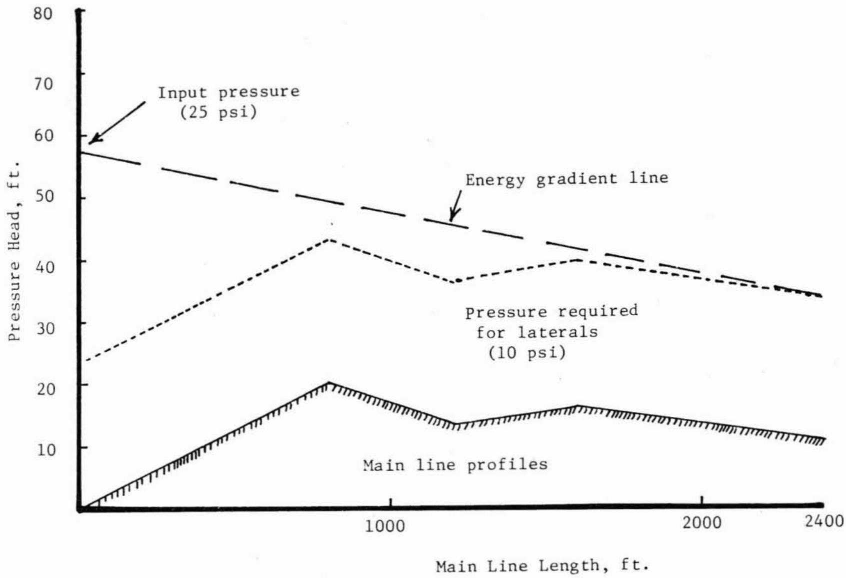



Figure 43. Main line profile and energy gradient line.

## DRIP IRRIGATION SYSTEM DESIGN USING METRIC UNITS

The developed design charts and design procedures can be made for metric units (*18*). The Williams and Hazen formula for smooth pipe (using $C = 150$) for metric units is shown in Equation 7 as

$$\Delta H = 15.27 \frac{Q^{1.852}}{D^{4.871}} \Delta L$$

in which $\Delta H$ and $\Delta L$ are expressed in meters, $Q$ is expressed in liters per second, and $D$ is expressed in centimeters. Equation 7 is used for developing the main line design chart and nomograph for designing lateral or submain with varying pipe sizes. The total energy drop by friction for a lateral or submain expressed in metric units is derived and shown in Equation 12 as

$$\Delta H = 5.35 \frac{Q_t^{\ 1.852}}{D^{4.871}} L$$

in which $Q_t$ is the total discharge (or inlet discharge) expressed in liters per second, $D$ is in centimeters, and $L$ and $H$ are expressed in meters.

## Lateral Line Design Charts for Uniform Slopes

The lateral line design charts were developed for two commonly used sizes, 12 and 16 mm (inside diameter) as shown in Figures 44 and 45.

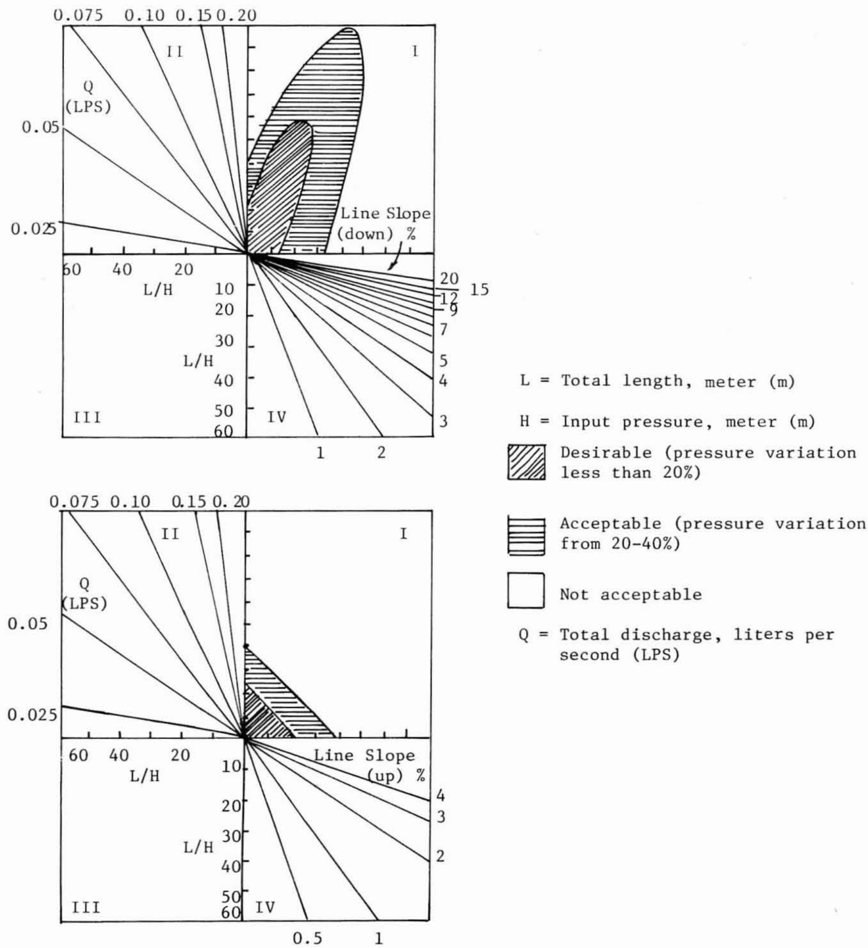



Figure 44. Drip irrigation design calculator (12 mm).

The design procedures are the same as presented in the section on the use of the general design charts.

## A General Design Chart for Uniform Slope for All Pipe Sizes

The general design charts presented earlier and shown in Figures 11, 12, and 14 and the design procedure using these charts can be used for lateral and submain design on uniform slope in metric units.

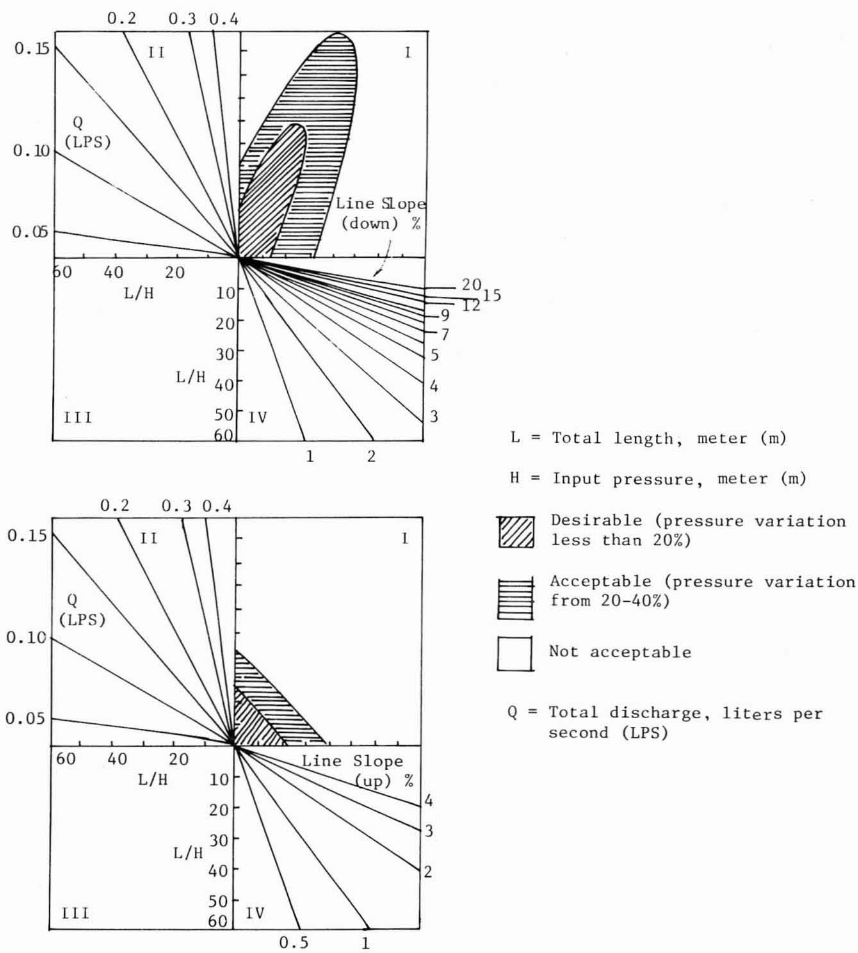



Figure 45. Drip irrigation design calculator (16 mm).

## Design Chart for Lateral Lines on Nonuniform Slopes

The dimensionless design chart for nonuniform slopes as given in Figure 17 combined with the nomograph as shown in Figure 14 can be used for lateral line design for nonuniform slopes. The design procedures are the same as presented in the earlier section on design for lateral lines on nonuniform slopes.

## Design Charts for Lateral and Submain Design with Varying Pipe Sizes

The nomograph shown in Figure 20 can be used to design laterals and submains with varying pipe sizes for both uniform and nonuniform slopes. The design procedures are the same as presented in the earlier section on design for laterals and submains with varying pipe sizes.

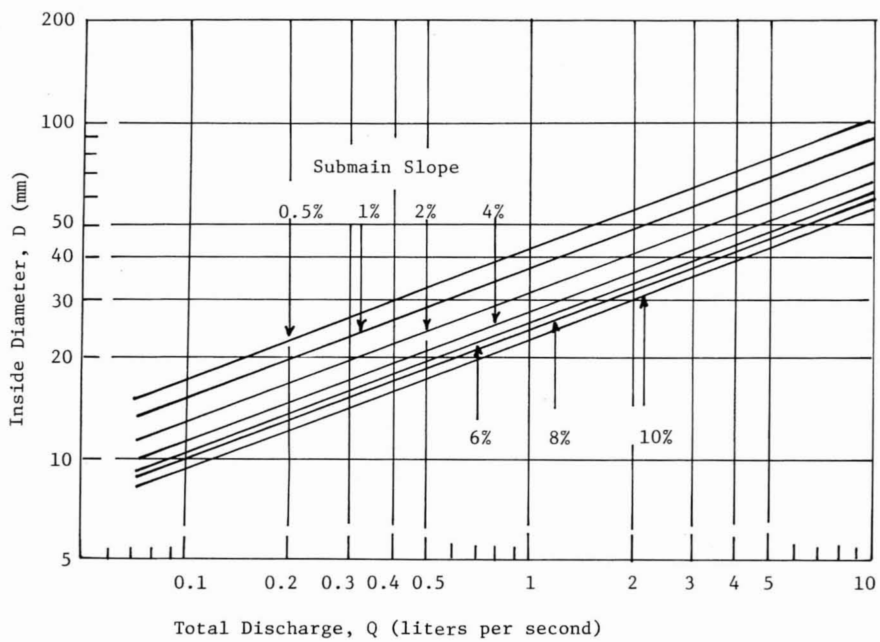



Figure 46. Submain design chart—slope equal or larger than 0.5 percent.

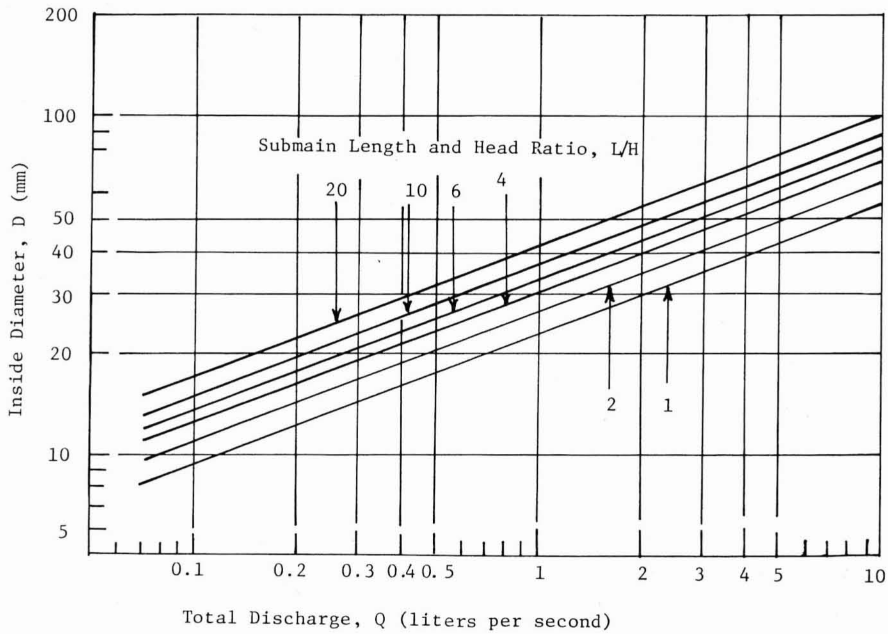



Figure 47. Submain design chart—slope less than 0.5 percent and allowable pressure variation 10 percent.

## Simplified Submain Design Charts

Two simplified submain design charts were developed and are shown in Figures 46 and 47. Figure 46 is designed for submain slopes equal to or larger than 0.5 percent and Figure 47 is designed for submain slopes less than 0.5 percent. The design procedures, including the irregular-shaped field case, are the same as presented in the section on submain design for single size on uniform downslopes or zero slope and the section on submain design for irregular-shaped fields.

## Design Chart for Drip Irrigation Main Lines

The nomograph similar to Figure 33 was plotted for main line design in metric units as shown in Figure 48. The design procedures are the same as presented in the section on a straight energy gradient line.

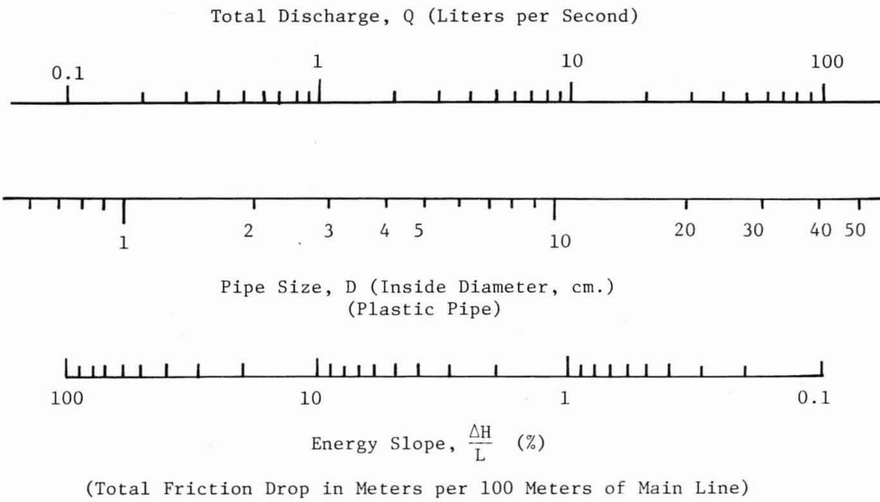



Figure 48. Nomograph for drip irrigation main line design in metric units.

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